
Sherburne SITE Report

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EnviroMetal Technologies, Inc.

**Metal-Enhanced Dechlorination of
Volatile Organic Compounds
Using an In-Situ Reactive Iron Wall**

Innovative Technology Evaluation Report

National Risk Management Research Laboratory
Office of Research and Development
U.S. Environmental Protection Agency
Cincinnati, Ohio 45268



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Notice

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Foreword

The U. S. Environmental Protection Agency (EPA) is charged by Congress with protecting the Nation's land, air, and water resources. Under a mandate of national environmental laws, the Agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to nurture life. To meet this mandate, EPA's research program is providing data and technical support for solving environmental problems today and building a science knowledge base necessary to manage our ecological resources wisely, understand how pollutants affect our health, and prevent or reduce environmental risks in the future.

The National Risk Management Research Laboratory is the Agency's center for investigation of technological and management approaches for reducing risks from threats to human health and the environment. The focus of the Laboratory's research program is on methods for the prevention and control of pollution to air, land, water and subsurface resources; protection of water quality in public water systems; remediation of contaminated sites and groundwater; and prevention and control of indoor air pollution. The goal of this research effort is to catalyze development and implementation of innovative, cost-effective environmental technologies; develop scientific and engineering information needed by EPA to support regulatory and policy decisions; and provide technical support and information transfer to ensure effective implementation of environmental regulations and strategies.

This publication has been produced as part of the Laboratory's strategic long-term research plan. It is published and made available by EPA's Office of Research and development to assist the user community and to link researchers with their clients.

E. Timothy Oppelt, Director
National Risk Management Research Laboratory

Abstract

EnviroMetal Technologies, Inc. (**ETI**), of Guelph, Ontario, Canada has commercialized a metal-enhanced dechlorination technology that the University of Waterloo, Canada developed to treat aqueous media contaminated with chlorinated volatile organic compounds (**VOCs**). The technology employs an electrochemical process that involves the oxidation of a reactive, granular iron medium to induce reductive dechlorination of chlorinated **VOCs**.

The Superfund Innovative Technology Evaluation (**SITE**) Program evaluated an in-situ application of the technology during a 6-month demonstration at a confidential site in central New York in 1995. For the demonstration of the in-situ system, the technology was constructed as a subsurface, reactive iron wall that fully penetrated a shallow sand and gravel aquifer. The top of the wall was above the highest average seasonal groundwater level, about 3 feet below grade, and was covered with a layer of native topsoil. The wall extended downward from the top of the saturated zone and was situated on top of an underlying, confining clay layer. The reactive iron wall, referred to as the "gate," was oriented perpendicular to the groundwater flow direction and was flanked by impermeable sheet piling wings which also fully penetrated the aquifer. The sheet piling formed a "funnel," creating a hydraulic barrier that diverted groundwater flow from a 24-foot-wide upgradient area through the gate, and prevented untreated groundwater from flowing around the gate and mixing with treated groundwater on the downgradient side.

During the demonstration, **SITE** Program personnel collected independent data to evaluate the technology's performance with respect to primary and secondary objectives. Groundwater samples were collected at locations on the upgradient (influent) and downgradient (effluent) sides of the iron, and also from locations within the iron. The groundwater samples were analyzed for **VOCs** to evaluate the technology's ability to reduce chlorinated **VOC** concentrations to applicable regulatory levels. The efficiency with which the system removed certain chlorinated **VOCs** was evaluated. Other data were collected to provide information about the dechlorination process, as well as costs and operating and maintenance requirements for the system.

The results of the sample analyses indicated that the technology significantly reduced the concentrations of chlorinated **VOCs** in groundwater passing through the gate. These chlorinated **VOCs** included trichloroethene (**TCE**), **cis-1,2-dichloroethene (cDCE)**, and vinyl chloride (**VC**). All average critical parameter effluent concentrations, and 86 out of 90 individual critical parameter measurements, achieved the applicable U.S. Environmental Protection Agency (**EPA**) maximum contaminant levels or New York State Department of Environmental Conservation target standards. Removal efficiencies for **TCE**, **cDCE**, and **VC** were consistently greater than 90 percent. The results indicated no decrease in removal efficiency or other significant changes in system performance over the 6-month demonstration period.

EPA SITE Program personnel prepared this Innovative Technology Evaluation Report (**ITER**) to present the results of the **SITE** Program demonstration. The **ITER** evaluates the ability of the in-situ application of the metal-enhanced dechlorination technology to treat chlorinated **VOCs** in contaminated groundwater based on the demonstration results. Specifically, this report discusses performance and economic data collected by **SITE** Program personnel, and also presents case studies and additional information about the technology provided by **ETI**.

Contents

List of Figures	viii
List of Tables	x
Acronyms, Abbreviations, and Symbols	xi
Conversion Factors	xiv
Acknowledgments	xv
Executive Summary	1
1 Introduction	6
1.1 Description of the SITE Program and Reports	6
1.1.1 Purpose, History, and Goals of the SITE Program	6
1.1.2 Documentation of SITE Demonstration Results	7
1.2 Background of the Metal-Enhanced Dechlorination Technology in the SITE Program	8
1.3 Technology Description	8
1.3.1 Process Chemistry	8
1.3.2 General Application and Design of Metal-Enhanced Process Systems	9
1.3.3 Advantages and Innovative Features of the Metal-Enhanced Dechloronation Process ..	10
1.4 Applicable Wastes	10
1.5 Overview of In-Situ, Metal-Enhanced Dechlorination Technology SITE Demonstration	12
15.1 Site Background	12
15.2 Technology Design	12
15.3 Technology and Monitoring System Construction	12
15.4 Treatment System Operation	16
15.5 SITE Demonstration Objectives	16
15.6 Demonstration Procedures	17
1.6 Postdemonstration Activities	18
1.7 Key Contacts	18
2 Technology Effectiveness Analysis	20
2.1 SITE Demonstration Results	20
2.1.1 Objective P- 1: Compliance with Applicable Effluent Target Levels	23
2.1.2 Objective P-2: Critical Parameter Removal Efficiency	23
2.1.3 Objective S-1: Critical Parameter Concentrations as a Function of Sampling Location (Distance)	25

Contents (continued)

2.1.4	Objective S-2: Noncritical VOCs, Metals, and Other Inorganic Parameters	29
2.1.5	Objective S-3: Eh, DO, pH, Specific Conductivity, and Temperature	36
2.1.6	Objective S-4: Biological Microorganism Growth	40
2.1.7	Objective S-5: Operating and Design Parameters	40
2.2	Additional Performance Data	43
2.2.1	Borden Site	46
2.2.2	California Semiconductor Facility	46
2.2.3	Belfast, Northern Ireland Facility	46
3	Technology Applications Analysis	47
3.1	Factors Affecting Performance	47
3.1.1	Feed Waste Characteristics	47
3.1.2	Hydrogeologic Characteristics	48
3.1.3	Operating Parameters	49
3.1.4	Maintenance Requirements	50
3.2	Site Characteristics and Support Requirements	51
3.2.1	Site Access, Area, and Preparation Requirements	51
3.2.2	Climate Requirements	51
3.2.3	Utility and Supply Requirements	52
3.2.4	Required Support Systems	52
3.2.5	Personnel Requirements	52
3.3	Material Handling Requirements	52
3.4	Technology Limitations	53
3.5	Potential Regulatory Requirements	54
3.5.1	Comprehensive Environmental Response, Compensation, and Liability Act	54
3.5.2	Resource Conservation and Recovery Act	56
3.5.3	Clean Water Act	57
3.5.4	Safe Drinking Water Act	57
3.5.5	Clean Air Act	57
3.5.6	Mixed Waste Regulations	58
3.5.7	Occupational Safety and Health Administration	58
3.6	State and Community Acceptance	58
4	Economic Analysis	59
4.1	Factors Affecting Costs	62
4.2	Assumptions Used in Performing the Economic Analysis	62
4.3	Cost Categories	64
4.3.1	Site Preparation Costs	64

Contents (continued)

4.3.2	Permitting and Regulatory Costs	66
4.3.3	Mobilization and Startup Costs	66
4.3.4	Capital Equipment Costs	66
4.3.5	Labor Costs	67
4.3.6	Supply costs	67
4.3.7	Utility Costs	67
4.3.8	Effluent Treatment and Disposal Costs	68
4.3.9	Residual Waste Shipping and Handling Costs	68
4.3.10	Analytical Services Costs	68
4.3.11	Equipment Maintenance Costs	68
4.3.12	Site Demobilization Costs	69
4.4	Economic Analysis Summary	69
5	Technology Status and Implementation	73
6	References	76

Appendix

A Vendor's Claims for the Technology

B Case Studies

C Summary of Analytical Data from the Demonstration of the In-Situ Metal-Enhanced Dechlorination Process: June 1995-December 1995.

Figures

1-1	Site Demonstration Area Layout	14
1-2	Plan and Profile Views of Funnel and Gate	15
2-1	Critical VOC Removal Efficiency Over Time	25
2-2	Critical VOCs vs. Distance-June	26
2-3	Critical VOCs vs. Distance-July	26
2-4	Critical VOCs vs. Distance-August	27
2-5	Critical VOCs vs. Distance-October.. ..	27
2-6	Critical VOCs vs. Distance-November	28
2-7	Critical VOCs vs. Distance-December	28
2-8	Summary of Calcium Data Over Time	31
2-9	Summary of Magnesium Data Over Time	31
2-10	Average Calcium and Magnesium Values vs. Distance	31
2-11	Summary of Iron Data Over Time	32
2-12	Summary of Manganese Data Over Time	32
2-13	Average Iron and Manganese Values vs. Distance	32
2-14	Summary of Barium Data Over Time	34
2-15	Summary of Bicarbonate Alkalinity Data Over Time.....	34
2-16	Average Bicarbonate Alkalinity and pH vs. Distance.. ..	34
2-17	Summary of Sulfate Data Over Time	35
2-18	Summary of Total Nitrate/Nitrite Data Over Time	35
2-19	Average Sulfate and Total Nitrate/Nitrite Values vs. Distance	35
2-20	Summary of pH Data Over Time.....	37
2-21	Average pH Values vs. Distance	37
2-22	Summary of Specific Conductivity Data Over Time	38
2-23	Average Specific Conductivity Values vs. Distance	38
2-24	Average Groundwater Temperature in Iron Wells vs. Time	39
2-25	Summary of Eh Data Over Time	39
2-26	Average Eh Values vs. Distance	39

Figures (continued)

2-27	Total Phospholipid Fatty Acids vs. Distance	41
2-28	Piezometric Elevations-December 1995	45
4-1	Distribution of Fixed Costs for Continuous Wall	71
4-2	Distribution of Annual Variable Costs for Continuous Wall	71
4-3	Distribution of Fixed Costs for Funnel and Gate System	72
4-4	Distribution of Annual Variable Costs for Funnel and Gate System	72

Tables

ES-1	Super-fund Feasibility Study Evaluation Criteria for the Metal-Enhanced Dechloronation Technology	4
1-1	Correlation Between Super-fund Feasibility Evaluation Criteria and ITER Sections	7
1-2	Comparison of Technologies for Treating Chlorinated VOCs in Water	11
1-3	System Design Criteria and Applicable Effluent Standards	13
2-1	Demonstration Results with Respect to Objectives	21
2-2	Summary of Critical VOC Concentrations at Effluent Sampling Locations	22
2-3	Summary of Critical Parameter Removal Efficiency: July-December 1995	24
2-4	Summary of Operating and Design Parameters	42
2-5	Piezometric Data.....	44
3-1	Summary of Environmental Regulations	55
4-1	Estimated Costs Associated with the Metal-Enhanced Dechloronation Technology: Continuous Wall System	60
4-2	Estimated Costa Associated with the Metal-Enhanced Dechloronation Technology: Funnel and Gate System	61

Acronyms, Abbreviations, and Symbols

AEA	Atomic Energy Act
ARAR	Applicable or Relevant and Appropriate Requirement
BGS	Below ground surface
CAA	Clean Air Act
CaCO ₃	Calcium carbonate
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CFR	Code of Federal Regulations
Cl ⁻	Chloride ion
CO ₃ ²⁻	Carbonate ion
DCA	1,1-Dichloroethane
cDCE	cis-1,2-Dichloroethene
CWA	Clean Water Act
1,2-DCE	1,2-Dichloroethene (general; undifferentiated for cis- and trans- isomers)
DO	Dissolved oxygen
DOE	Department of Energy
Eh	Oxidation-reduction potential
EPA	U.S. Environmental Protection Agency
ETI	EnviroMetal Technology, Inc.
Fe	Zero-valent iron
Fe ²⁺	Ferrous iron
Fe ³⁺	Ferric iron
Fe(OH) ₂	Ferrous hydroxide
Fe(OH) ₃	Ferric hydroxide
FeCO ₃	Ferrous carbonate or siderite
ft	Feet
gpd	Gallons per day
H ⁺	Hydrogen ion
H ₂ (g)	Hydrogen gas
HCO ₃	Bicarbonate ion
in	Inch
ITER	Innovative Technology Evaluation Report

Acronyms, Abbreviations, and Symbols (continued)

LCL	Lower confidence limit
LDR	Land disposal restrictions
m	Meter
MCL	Maximum contaminant level
MDL	Method detection limit
mg/L	milligram per liter
MnO₂(s)	Manganese dioxide (solid)
msl	mean sea level
NAPL	Nonaqueous-phase liquid
NESHAP	National Emission Standards for Hazardous Air Pollutants
NOEL	Nonobservable Effect Level
NPDES	National Pollutant Discharge Elimination System
NRC	Nuclear Regulatory Commission
NRMRL	National Risk Management Research Laboratory
NSPS	New Source Performance Standard
NYSDEC	New York State Department of Environmental Conservation
O&M	Operating and maintenance
OH	Hydroxyl ion
ORD	U.S. EPA Office of Research and Development
OSHA	Occupational Safety and Health Act
OSWER	Office of Solid Waste and Emergency Response
PCB	Polychlorinated biphenyl
PCE	Tetrachloroethene
pcf	Pounds per cubic foot
PLFA	Phospholipid fatty acid
POTW	Publicly Owned Treatment Works
ppbv	Parts per billion by volume
ppe	Personnel protective equipment
QAPP	Quality assurance project plan
QA/QC	Quality assurance/quality control
RCRA	Resource Conservation and Recovery Act
RE	Removal efficiency
SARA	Super-fund Amendments and Reauthorization Act
SDWA	Safe Drinking Water Act
S&W	Stearns & Wheler, L.L.C.
SITE	Super-fund Innovative Technology Evaluation
TCA	1,1,1-Trichloroethane
TCE	Trichloroethene
TCL	Target compound list

Acronyms, Abbreviations, and Symbols (continued)

TCLP	Toxicity characteristic leaching procedure
tDCE	Trans-1,2-Dichloroethene
TER	Technology evaluation report
TIC	Tentatively identified compound
TSCA	Toxic Substances Control Act
$\mu\text{g/L}$	Micrograms per liter
v c	Vinyl chloride
VOC	Volatile organic compound
WQS	Water quality standards

Conversion Factors

	<i>To Convert From</i>	<i>To</i>	<i>Multiply By</i>
Length	inch	centimeter	2.54
	foot	meter	0.305
	mile	kilometer	1.61
Area:	square foot	square meter	0.0929
	acre	square meter	4,047
Volume:	gallon	liter	3.78
	cubic foot	cubic meter	0.0283
Mass:	pound	kilogram	0.454
Energy:	kilowatt-hour	megajoule	3.60
Power:	kilowatt	horsepower	1.34
Temperature:	("Fahrenheit - 32)	"Celsius	0.556

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Executive Summary

EnviroMetal Technologies, Inc. (ETI), has commercialized a metal-enhanced dechlorination technology originally developed by the University of Waterloo, Canada to dechlorinate chlorinated volatile organic compounds (VOCs) such as chlorinated methanes, ethanes, and ethenes in aqueous media. An in-situ application of the technology was demonstrated under the U.S. Environmental Protection Agency's (EPA) **Superfund** Innovative Technology Evaluation (SITE) Program at a confidential site in central New York state from June through December 1995.

The purpose of this Innovative Technology Evaluation Report is to present information that will assist Super-fund decision-makers in evaluating this technology's suitability for remediating a particular hazardous waste site. The report provides an introduction to the SITE Program and the metal-enhanced dechlorination process and discusses the demonstration objectives and activities (Section 1); evaluates the technology's effectiveness (Section 2); analyzes key factors pertaining to application of this technology (Section 3); analyzes the costs of using the technology to treat groundwater contaminated with chlorinated VOCs (Section 4); summarizes the technology's current status (Section 5); and presents a list of references (Section 6). Vendor's claims and additional performance data for the technology, and case studies of other applications of the metal-enhanced dechlorination technology are included in Appendices A and B, respectively.

This executive summary briefly summarizes the information discussed in the ITER and evaluates the technology with respect to the nine criteria used in Super-fund feasibility studies.

Technology Description

ETI claims that the technology can treat chlorinated methanes, ethanes, and ethenes over a wide range of

concentrations. The metal-enhanced dechlorination technology involves oxidation of iron and reductive dechlorination of chlorinated VOCs in aqueous media. A reactive, zero-valent, granular iron medium oxidizes and thereby induces dechlorination of chlorinated VOCs, yielding simple hydrocarbons and inorganic chlorides as by-products. The technology can be installed in-situ as a permeable treatment wall, or can be applied aboveground in a reactor. For in-situ applications, a reactive iron wall is constructed by excavating a trench and backfilling it with the reactive iron medium. The wall is oriented perpendicular to the flow path of groundwater contaminated with chlorinated VOCs. For some applications, a "funnel and gate" configuration may be used. The "funnel" consists of a sealable joint sheet pile or slurry wall that directs water to the iron wall, or "gate," and also prevents untreated groundwater from flowing around the gate. The impermeable funnels allow containment and treatment of a contaminant plume without constructing an iron wall across the plume's entire width.

Overview of the Metal-Enhanced Dechlorination Technology SITE Demonstration

The SITE demonstration of the in-situ, metal-enhanced dechlorination process occurred between June and December 1995. An in-situ funnel and gate system was used to treat groundwater in a shallow, unconsolidated, sand and gravel aquifer. The demonstration site was a field adjacent to an inactive manufacturing facility in central New York. Groundwater in the shallow aquifer generally flows westward from the manufacturing facility and across the demonstration site. Former manufacturing operations at the facility included metal plating and finishing. Chemicals used in the metal finishing operations apparently resulted in groundwater contamination; past groundwater samples collected at the facility and at the demonstration site indicated the presence of chlorinated VOCs in the aquifer. Chlorinated

groundwater include trichloroethene (TCE), cis-1,2-dichloroethene (cDCE), and vinyl chloride (VC).

For the SITE Program demonstration, a pilot-scale metal-enhanced dechlorination system was constructed in the field bordering the downgradient side of the facility to treat groundwater as it moved off site. The system consisted of a 12-foot-wide in-situ reactive iron wall (the gate) oriented perpendicular to the groundwater flow direction. The iron wall was about 3-feet thick, and fully penetrated the sand and gravel aquifer. The top of the wall was above the average seasonal high groundwater level, about 3 feet below ground surface, and was covered with a layer of native topsoil. The wall extended down into an underlying, confining clay layer. The wall was flanked by 15-foot-long sections of impermeable sheet piling. These flanking sections created the funnel that directed flow toward the gate and prevented untreated groundwater from bypassing the reactive iron wall and mixing with treated water in the demonstration study area. According to ETI, the system captured about a 24-foot-wide portion of the contaminant plume.

The primary objectives of the SITE demonstration were as follows:

- Determine whether treated groundwater from the in-situ, permeable treatment wall meets NYSDEC groundwater standards and federal MCL effluent standards for the critical contaminants: tetrachloroethene (PCE), TCE, 1,1, 1-trichloroethane (TCA), cDCE, trans-1,2-dichloroethene (tDCE), and VC
- Determine the removal efficiency (RE) of critical contaminants from groundwater

The secondary objectives of the demonstration were:

- Determine concentration gradients of critical contaminants as groundwater passes through the in-situ treatment wall
- Examine total metals, chloride, sulfate, nitrate, bicarbonate, and non-critical VOC concentrations in groundwater as it passes through the treatment wall
- Document geochemical conditions (specific conductance, oxidation/reduction potential (Eh), pH,

dissolved oxygen (DO), and temperature) in groundwater passing through the treatment wall

- Examine biological microorganism growth in the reactive iron medium and in upgradient and downgradient groundwater
- Document operating and design parameters (initial weight, volume, and density of the reactive iron medium, groundwater flow velocity) of the in-situ, permeable treatment wall

During the demonstration, groundwater samples were collected from monitoring wells upgradient from, in, and downgradient from the reactive iron wall. Groundwater samples were collected and analyzed for the six critical VOCs during June, July, August, October, November, and December 1995. Samples were also collected and analyzed for noncritical parameters to support secondary objectives. Field measurements of groundwater elevations, dissolved oxygen (DO), temperature, specific conductance, pH, and oxidation-reduction potential (Eh) were also performed.

Samples indicated that influent groundwater contained TCE at concentrations ranging from about 32 to 330 micrograms per liter ($\mu\text{g/L}$); cDCE at concentrations ranging from about 98 to 550 $\mu\text{g/L}$; and VC at concentrations ranging from about 5 to 79 $\mu\text{g/L}$. Lower concentrations (less than 15 $\mu\text{g/L}$ of TCA and 1,1-dichloroethane (DCA) were also typically present.

Based on SITE Program data and postdemonstration data obtained by ETI, the average groundwater flow velocity through the iron was probably in the range of about 0.4 to 1 foot per day. Assuming the high (conservative) velocity, the treatment system design allowed for a minimum contact time between groundwater and the reactive iron medium of about 3 days. Based on the range of possible groundwater flow velocities, between 29,000 and 73,000 gallons of groundwater was treated between the time the system was constructed (May 1995) and the SITE demonstration was completed (December 1995).

SITE Demonstration Results

The following items summarize the significant results of the SITE demonstration:

- Average critical contaminant concentrations for the downgradient wells were all below the target.

- Average critical contaminant concentrations for the downgradient wells were all below the target MCLs and NYSDEC standards. Individual downgradient concentrations of critical VOCs were predominantly nondetect. Individual results for cDCE sporadically exceeded the NYSDEC criterion of 5 µg/L; however, concentrations were significantly reduced from influent concentrations.
- Minimum overall average REs were high for all critical parameters present at significant concentrations in the influent groundwater. RE was greater than 99.0 percent for TCE, 98.6 percent for cDCE, and greater than 96.0 percent for VC. Actual removal efficiencies may have been higher, but are unknown, because the REs were calculated using the detection limit of 1 µg/L to represent effluent values that were below detectable limits.
- Although significant concentrations of multi-chlorinated ethenes (such as TCE) were reduced by the technology, there was no detectable increase in dechlorination byproducts such as cDCE, tDCE, or VC. Concentrations of all of these compounds in the downgradient wells were lower than in upgradient wells, and were nondetectable in most cases. These observations indicate that the reactive iron wall dechlorinated the original compounds and the byproducts.
- The concentrations of metals such as calcium and magnesium generally decreased as groundwater moved through the iron wall, coinciding with an increase in pH, suggesting precipitation of metal compounds.
- Bicarbonate alkalinity decreased as groundwater flowed through the wall. This observation, combined with the metals behavior and the changes in geochemical parameters, also suggests that inorganic compounds were precipitating in the reactive iron.
- Total PLFA analyses indicated that total microbial activity in water in the reactive iron wall was not significantly higher than in water in the natural aquifer materials upgradient or downgradient from the wall. This observation indicates that the process is abiotic.
- No significant operating problems were noted during the SITE demonstration. According to ETI, the most significant potential long-term problem with respect to operation appears to be the loss of porosity or iron reactivity due to precipitates. However, although inorganic compounds appeared to be precipitating during the SITE demonstration, there was no noticeable decrease in system performance over the 6-month demonstration.
- Interpretation of piezometric data collected during the demonstration was complicated by the extremely low horizontal gradient and close spacing of the monitoring wells. For this reason, the actual flow velocity through the iron is unknown, but appears to have been in the range of about 0.4 to 1 foot per day.

Economics

Using information obtained from the SITE demonstration, ETI, and other sources, an economic analysis examined 12 cost categories for a scenario in which the metal-enhanced dechlorination technology was applied at full scale to treat contaminated groundwater at a Superfund site for a 20-year period. The cost estimate assumed that the site hydrogeology and the general types and concentrations of chlorinated VOCs were the same as those encountered during the New York demonstration. Based on these assumptions, the total costs were estimated to be about \$18 per 1,000 gallons of groundwater treated for a continuous wall, and \$20 per 1,000 gallons treated for a full-scale funnel and gate system. However, total cost and cost per gallon for using this technology are highly site-specific. Also, because this passive technology simultaneously controls off-site contaminant migration and removes contaminants, it combines beneficial features of containment systems and treatment systems.

Superfund Feasibility Study Evaluation Criteria for the Metal-Enhanced Dechlorination Technology

Table ES-1 briefly discusses an evaluation of the in-situ metal-enhanced dechlorination technology with respect to the nine evaluation criteria used for Superfund feasibility studies when considering remedial alternatives at Superfund sites (EPA 1988c).

Table ES-I. Superfund Feasibility Study Evaluation Criteria for the Metal-Enhanced Dechlorination Technology

Criterion	Discussion
Overall Protection of Human Health and the Environment	<ul style="list-style-type: none"> • The technology is expected to protect human health and the environment by treating water to significantly lower concentrations of chlorinated VOCs. • Protection of the environment at and beyond the point of discharge should be evaluated based on uses of the receiving water body, concentrations of residual contaminants and treatment by-products, and dilution factors.
Compliance with Applicable or Relevant and Appropriate Requirements (ARAR)	<ul style="list-style-type: none"> • The technology's ability to comply with existing federal, state, or local ARARs (for example, MCLs) should be determined on a site-specific basis. • The technology was able to meet target effluent concentrations based on federal maximum contaminant levels (MCL) and New York State Department of Environmental Conservation (NYSDEC) groundwater discharge standards for average downgradient concentrations of all critical parameters. After system performance stabilized, only four cDCE results out of 90 individual critical parameter analyses slightly exceeded NYSDEC levels.
Long-Term Effectiveness and Permanence	<ul style="list-style-type: none"> • Human health risk can be reduced to acceptable levels by treating groundwater to site-specific cleanup levels; the time needed to achieve cleanup goals depends primarily on contaminant characteristics and groundwater flow velocity. • The long-term effectiveness of the technology may depend on periodically replacing or treating the iron medium. • The treatment is permanent because the technology dechlorinates chlorinated VOCs to less chlorinated compounds. • Periodic review of treatment system performance is needed because application of this technology to contaminated groundwater at hazardous waste sites is relatively recent.
Reduction of Toxicity, Mobility, or Volume Through Treatment	<ul style="list-style-type: none"> • Target compounds are dechlorinated to less toxic substances by the technology; also, the concentrations of individual target compounds and the total concentrations of chlorinated VOCs are reduced.

Table ES-I. Superfund Feasibility Study Evaluation Criteria for the Metal-Enhanced Dechlorination Technology (continued)

Criterion	Discussion
Short-Term Effectiveness	<p>The technology appears to be able to reduce chlorinated VOC concentrations as groundwater passes through the system. However, the speed of treatment is somewhat limited by the natural groundwater flow velocity.</p>
Implementability	<ul style="list-style-type: none"> <li data-bbox="690 653 1446 842">• Appropriate hydrogeologic conditions should be present and well-defined to implement this technology. Currently, the technology is most easily implemented at shallow depths, and is best suited for aquifers having an underlying aquitard at less than 50 feet below ground surface. <li data-bbox="690 863 1446 926">• The site must be accessible to typical construction equipment and delivery vehicles. <li data-bbox="690 947 1446 1094">• The actual space requirements will depend on (1) the length of iron wall required to capture a contaminant plume, and (2) the thickness required to allow sufficient residence time for dechlorination. <li data-bbox="690 1115 1446 1178">• Site-specific requirements may dictate the need for additional services and supplies.
Cost	<ul style="list-style-type: none"> <li data-bbox="690 1199 1429 1461">• For a full-scale, 300-foot-long continuous iron wall operating for 20 years to treat a plume under the same general conditions observed at the New York site, fixed costs are estimated to be \$466,600. Annual operating and maintenance costs, including those for residual waste handling, analytical services, labor, and equipment maintenance, are estimated to be about \$20,900.
Community Acceptance	<ul style="list-style-type: none"> <li data-bbox="690 1482 1438 1713">• This criterion is generally addressed in the record of decision after community responses are received during the public comment period. However, because communities are not expected to be exposed to harmful levels of VOCs, noise, or fugitive emissions, community acceptance of the technology is expected to be relatively high.
State Acceptance	<ul style="list-style-type: none"> <li data-bbox="690 1734 1438 1860">• This criterion is generally addressed in the record of decision; state acceptance of the technology will likely depend on the long-term effectiveness of the technology.

Section 1 Introduction

This section describes the Super-fund Innovative Technology Evaluation (SITE) Program and the Innovative Technology Evaluation Report (ITER); provides background information on the **EnviroMetal Technologies, Inc. (ETI)**, metal-enhanced dechlorination technology; identifies wastes to which this technology may be applied; and provides a list of key contacts. This section also provides an overview of the SITE Program demonstration of the in-situ metal-enhanced dechlorination process.

1.1 Description of SITE Program and Reports

This section provides information about (1) the purpose, history, and goals of the SITE Program, and (2) the reports used to document SITE demonstration results.

1.1.1 Purpose, History, and Goals of the SITE Program

The primary purpose of the SITE Program is to advance the development and demonstration, and thereby establish the commercial availability, of innovative treatment technologies applicable to Super-fund and other hazardous waste sites. The SITE Program was established by the U.S. Environmental Protection Agency (EPA) Office of Solid Waste and Emergency Response (OSWER) and Office of Research and Development (ORD) in response to the Super-fund Amendments and Reauthorization Act of 1986 (SARA), which recognized the need for an alternative or innovative treatment technology research and demonstration program. The SITE Program is administered by ORD's National Risk Management Research Laboratory. The overall goal of the SITE Program is to carry out a program of research, evaluation, testing, development, and demonstration of alternative or innovative treatment technologies that may be used in

response actions to achieve more permanent protection of human health and welfare and the environment.

The SITE Program consists of four component programs: (1) the Demonstration Program, (2) the Emerging Technology Program, (3) the Monitoring and Measurement Technologies Program, and (4) the Technology Transfer Program. This ITER was prepared under the SITE Demonstration Program. The objective of the Demonstration Program is to provide reliable performance and cost data on innovative technologies so that potential users can assess a given technology's suitability for specific site cleanups. To produce useful and reliable data, demonstrations are conducted at hazardous waste sites or under conditions that closely simulate actual waste site conditions.

Information collected during a demonstration is used to assess the performance of the technology, the potential need for pretreatment and posttreatment processing of the waste, the types of wastes and media that may be treated by the technology, potential operating problems, and approximate capital and operating costs. Demonstration information can also provide insight into a technology's long-term operating and maintenance (O&M) costs and long-term application risks.

Each SITE demonstration evaluates a technology's performance in treating waste at a particular site. Successful demonstration of a technology at one site or on a particular waste does not ensure its success at other sites or for other wastes. Data obtained from the demonstration may require extrapolation to estimate a range of operating conditions over which the technology performs satisfactorily. Also, any extrapolation of demonstration data should be based on other information about the technology, such as information available from case studies.

Implementation of the SITE Program is a significant, ongoing effort involving ORD, OSWER, various EPA regions, and private business concerns, including technology developers and parties responsible for site remediation. The technology selection process and the Demonstration Program together provide objective and carefully controlled testing of field-ready technologies. Innovative technologies chosen for a SITE demonstration must be pilot- or full-scale applications and must offer some advantage over existing technologies; mobile technologies are of particular interest.

1.1.2 Documentation of SITE Demonstration Results

The results of each SITE demonstration are reported in an ITER and a Technology Evaluation Report (TER). Information presented in the ITER is intended to assist Superfund decision makers evaluating specific technologies for a particular cleanup situation. The in-situ metal-enhanced dechlorination technology has been evaluated against the nine criteria used for feasibility studies supporting the Superfund remedial process. The nine criteria are listed in Table 1-1 along with the sections of the ITER where information related to each criterion is discussed. The ITER represents a critical step in the

development and commercialization of a treatment technology. The report discusses the effectiveness and applicability of the technology and analyzes costs associated with its application. The technology's effectiveness is evaluated based on data collected during the SITE demonstration and from other case studies. The applicability of the technology is discussed in terms of waste and site characteristics which could affect technology performance, material handling requirements, technology limitations, and other factors for any application of the technology.

The purpose of the TER is to consolidate all information and records acquired during the demonstration. It contains both a narrative portion and tables and graphs summarizing data. The narrative portion includes discussions of predemonstration, demonstration, and postdemonstration activities as well as any deviations from the demonstration quality assurance project plan (QAPP) during these activities and their impact. The data tables and graphs summarize demonstration results relative to project objectives. The tables also summarize quality assurance and quality control (QA/QC) data and data quality objectives. The TER is not formally published by EPA. Instead, a copy is retained as a reference by the EPA project manager for responding to public inquiries and for recordkeeping purposes.

Table 1-1. Correlation Between Superfund Feasibility Evaluation Criteria and ITER Sections

Evaluation Criterion ^a	ITER Section
Overall protection of human health and the environment	2.1.1, 2.2.2, 3.5, 3.6
Compliance with ARARs	2.1.1; 3.5; 3.6
Long-term effectiveness and permanence	2.1.1; 2.1.2; 2.1.4; 2.2; 3.1
Reduction of toxicity, mobility, or volume through treatment	2.2.1; 2.2.2; 2.2.3
Short-term effectiveness	2.2.1; 2.2.2; 2.2
Implementability	1.6; 3.0; 5.0
cost	4.0
State acceptance	2.1.1; 3.5; 3.6
Community acceptance	2.1.1; 3.5; 3.6

Note: ^a Source: EPA 1988c

1.2 Background of the Metal-Enhanced Dechlorination Technology in the SITE Program

In 1993, the owner of the New York demonstration site and its consultant, Stearns & Wheeler, L.L.C. (S&W), responded to a solicitation from the SITE Program by submitting a proposal for the SITE Program to evaluate the metal-enhanced dechlorination process at the New York site. Through negotiations with the New York State Department of Environmental Conservation (NYSDEC) and ETI, the site owners and S&W proposed constructing a pilot-scale, in-situ treatment system employing the metal-enhanced dechlorination process. The pilot-scale system would be used to evaluate the technology's suitability to remediate a chlorinated VOC plume in groundwater at the site. SITE Program personnel participated in the evaluation of the technology by collecting independent data to evaluate system performance.

1.3 Technology Description

This section describes the principles of metal-enhanced dechlorination, the treatment system used for the technology, and advantages and innovative features of the technology.

1.3.1 Process Chemistry

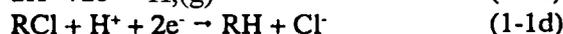
The metal-enhanced dechlorination technology employs an electrochemical process involving oxidation of iron and reductive dechlorination of VOCs in aqueous media. Although aluminum, copper, brass, standard steel, and zinc have also been shown to promote reductive dechlorination of VOCs, zero-valent iron has been chosen for use in large-scale applications of the technology. Iron is readily available, relatively inexpensive, and induces rapid dechlorination of organic compounds (O'Hannesin and Gillham 1992).

The technology induces conditions that cause substitution of chlorine atoms by hydrogen.

Because chlorinated aliphatic VOCs are in a relatively oxidized state, their reduction in the presence of reduced metals is thermodynamically favorable. The corrosion of zero-valent iron (Fe⁰) in contact with groundwater creates a highly reducing environment in solution, evidenced by a decline in oxidation/reduction potential (Eh). During the

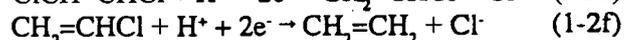
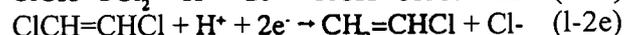
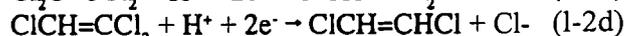
process the solution pH increases, the concentration of OH⁻ increases, and electrons are transferred from the metal to the chlorinated organic compound. Overall, the reactions cause hydrogen ions to replace the chlorine atom(s) of the chlorinated organic compound (Gillham 1996; Focht, Vogan and O'Hannesin 1996).

The reaction mechanism is not completely understood; several mechanisms have been proposed. According to Gillham and O'Hannesin (1994) the following equations may describe the reactions that take place in the presence of water, zero-valent iron (Fe⁰), and a chlorinated hydrocarbon (RCl):



In this series of equations, the conversion of Fe⁰ to ferrous iron (Fe²⁺), commonly known as corrosion, is described by Equation 1-1a. Equation 1-1b describes the ionization of water. The electrons released by the corrosion of iron (Equation 1-1a) react with hydrogen ions (H⁺) and R-Cl according to Equations 1-1c and 1-1d, resulting in the formation of Fe²⁺, hydroxyl ions (OH⁻), hydrogen gas [H₂(g)], nonchlorinated hydrocarbons (RH), and chloride ions (Cl⁻). While the ionization of water (equation 1-1b) accompanies the dechlorination process, it is unknown if this reaction is required for the overall dechlorination reaction to occur (Gillham and O'Hannesin 1994; Gilham 1996).

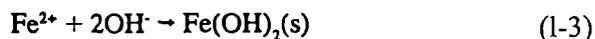
For multi-chlorinated VOCs such as tetrachloroethene (PCE), trichloroethene (TCE), or 1,2-dichloroethene (1,2-DCE), the progression of the dechlorination reaction is not completely understood. Chen (1995) proposed that the dechlorination of a multi-chlorinated VOC (in this case PCE) may follow a sequential mechanism, evidenced by the appearance of intermediate by-products such as TCE, 1,2-DCE, and vinyl chloride (VC), as shown in the following equations:



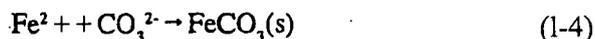
Others have proposed alternate reaction mechanisms. According to ETI, recent research has indicated that the dechlorination of PCE and TCE may involve multiple mechanisms. Focht, Vogan, and O'Hannesin (1996) report that for bench-scale studies involving dechlorination of TCE, only about 10 to 20 percent of the original mass of TCE typically appears as 1,2-DCE, and less than 1 percent appears as vinyl chloride (VC). Based on similar mass balance estimates, some researchers have suggested that the predominant dechlorination reaction mechanism may not be sequential, and may be due to a precipitous transfer of electrons from the iron to the organic contaminant molecule through direct contact (Gillham and O'Hannesin 1994; Gillham 1996). However, 1,2-DCE and VC are also dechlorinated by reactive iron, and it is possible that these compounds are generated and destroyed too rapidly to allow detection of the full amounts generated.

For long-term remediation projects using this technology, decision makers and technology designers should be aware of the possibility of formation of by-products, such as 1,2-DCE and VC if multi-chlorinated compounds such as TCE or PCE are incompletely dechlorinated. However, this effect was not observed during the New York demonstration. The results of the New York demonstration indicated that significant decreases in TCE, cDCE, and VC occurred as groundwater moved throughout the reactive iron. No measurable increase in the amounts of expected dechlorination by-products (cDCE and VC) was observed; effluent concentrations of cDCE and VC were significantly less than influent levels during all months of testing (see Section 2.1.1).

Past research by ETI and others has also suggested that when the process is used to dechlorinate VOCs in groundwater that also contains soluble metal species, the dechlorination reaction is accompanied by precipitation of metal compounds from the groundwater. If no oxygen is present and pH becomes sufficiently high, ferrous hydroxide [Fe(OH)₂] may precipitate:



Carbonate (CO₃²⁻) may react with Fe²⁺ to form ferrous carbonate (FeCO₃), known as siderite:



Because iron-hydroxide and iron-carbonate precipitates are formed during treatment, the concentrations of

dissolved iron in the effluent are expected to be relatively low. Depending on concentrations of soluble metal compounds in influent groundwater, other carbonates such as calcium carbonate, may precipitate (Gillham 1996; Reardon 1995).

1.3.2 General Application and Design of Metal-Enhanced Dechlorination Process Systems

The metal-enhanced dechlorination process uses a reactive, zero-valent, granular iron medium to perform in-situ remediation of groundwater contaminated with chlorinated VOCs. Chlorinated VOCs are among the most pervasive groundwater contaminants at Super-fund and other hazardous waste sites.

The technology is typically installed as a permeable subsurface wall; the dechlorination reaction described in Section 1.3.1 occurs as groundwater flows through the wall. For this reason, optimal site conditions for application of this technology include shallow depth to groundwater and the presence of a confining layer beneath the contaminated aquifer. Also, installation of in-situ systems may require excavation to the underlying confining layer, and therefore the thickness and depth to the bottom of the saturated zone are determining factors for application of this technology.

The technology may be installed as a continuous, reactive subsurface wall, or as a configuration of alternating "funnels" and "gates". For funnel and gate configurations, impermeable sections of sealable joint sheet piling or slurry walls contain the contaminant plume and funnel groundwater flow through the iron wall or gate. The number and dimensions of the gates required depends on the size of the contaminant plume and hydrogeologic factors such as gradient, flow velocity, and saturated thickness.

The metal-enhanced dechlorination process may also be installed in an aboveground reactor, supporting conventional pump-and-treat operations. Aboveground reactors may be particularly suited to short-term, small-scale remediation projects requiring treatment of relatively small amounts of groundwater, or for sites where excavation and construction activities in the immediate vicinity of a contaminant plume are impractical. For aboveground applications, groundwater is extracted from the aquifer and pumped to the reactor for

treatment. The SITE Program evaluated a pilot-scale aboveground reactor at a site in New Jersey in 1994 and 1995. (The results of the aboveground reactor demonstration were reported in a previous ITER (EPA 1997).

The in-situ system design used during the SITE demonstration was a subsurface treatment cell consisting of one reactive iron wall flanked by two impermeable sheet piling sections, as shown in Figure 1-1. The funnel and gate system used was not designed to capture and treat the entire chlorinated VOC plume present in groundwater at the site, but rather to evaluate the technology's effectiveness at pilot scale. Pilot scale systems allow for measurement, control, modification, and optimization of design and operating parameters before construction of the full scale system. The system may eventually be expanded or replaced by a full scale system consisting of several alternating funnel and gate sections or a continuous iron wall to capture and treat the entire plume (ETI 1996d).

1.3.3 Advantages and Innovative Features of the Metal-Enhanced Dechlorination Process

Table 1-2 compares the in-situ metal-enhanced dechlorination technology to several other treatment options for water contaminated with chlorinated VOCs. Common ex-situ methods for treating groundwater contaminated with solvents and other organic compounds include air stripping, steam stripping, carbon adsorption, biological treatment, chemical oxidation, and photolysis. The metal-enhanced dechlorination technology offers a major advantage over some of these more conventional treatment technologies because the process destroys hazardous substances rather than transferring them to another medium, such as activated carbon or air.

The technology can treat groundwater with relatively high concentrations of chlorinated VOCs. For example, as indicated by the case studies in Appendix B, the technology has been used to treat groundwater containing chlorinated VOCs at concentrations up to about 300,000 $\mu\text{g/L}$. The contaminant loading mass and rate, relative to the available iron surface area in the system, affects system performance (see Section 3.1); higher contaminant concentrations may increase the amount of iron required to completely dechlorinate a substance and all associated dechlorination by-products. However, the reactive iron is

a by-product of metal machining and finishing operations, and is therefore readily-available and relatively inexpensive (Gillham 1995; ETI 1996d).

A significant advantage of the metal-enhanced dechlorination process over conventional pump- and-treat technologies is that it can treat groundwater in-situ, eliminating the need to extract contaminated groundwater before treatment. In-situ systems also eliminate the need to manage treated effluent that can lead to relatively high costs for conventional, ex-situ technologies. Also, in-situ systems eliminate the need for intrusive surface structures, allowing less restricted long-term use of the area where the system is installed.

Once installed, operating requirements are minimal. Because the technology is a passive treatment process there are no moving parts and no utilities are required. The system is installed below ground, and therefore is not subject to the effects of adverse weather conditions.

Long-term (greater than 5 years) data for field applications of in-situ systems are unavailable at the time of this report; therefore, the useful life of the reactive iron under field conditions is unknown. Precipitates may reduce the porosity of the iron or block the available reactive surface area. The results of a previous SITE Program demonstration of the aboveground reactor indicated that a portion of the iron would periodically require mechanical mixing, treatment, or replacement to maintain target removal efficiency levels (EPA 1997). However, no decrease in the in-situ system's performance was detectable over the 6-month New York demonstration.

1.4 Applicable Wastes

According to ETI, existing performance data indicates that the metal-enhanced dechlorination process is applicable to a wide range of chlorinated methanes, ethanes, and ethenes in water (Focht, Vogan, and O'Hannesin 1996). Research is currently underway at other sites to determine the technology's ability to reduce concentrations of other types of substances such as hexavalent chromium (Puls, Powell, and Paul 1995; ETI 1996c). At the New York site, the SITE Program demonstration primarily examined the technology's ability to treat six critical contaminants: PCE, TCE, cis- 1,2-dichloroethene (cDCE), trans- 1,2-dichloroethene (tDCE), 1,1,1-trichloroethane (TCA); and v c.

Table 1-2. Comparison of Technologies for Treating Chlorinated VOCs in Water

Technology	Advantages	Disadvantages
Air stripping	Effective for high concentrations; can treat a wide range of VOCs ; mechanically simple; relatively inexpensive	Inefficient for low concentrations; VOCs discharged to air or require secondary "polishing"
Steam stripping	Effective for all concentrations and many types of VOCs	VOCs discharged to air or require secondary "polishing"; high energy consumption
Air stripping with carbon adsorption of vapors	Effective for high concentrations and many types of VOCs	Sometimes inefficient for low concentrations; requires disposal or regeneration of spent carbon; relatively expensive
Carbon adsorption	Low air emissions; effective for high concentrations	Sometimes inefficient for low concentrations; requires disposal or regeneration of spent carbon; relatively expensive
Biological treatment (ex-situ)	Low air emissions; relatively inexpensive	Inefficient for high concentrations; slow rates of removal; sludge treatment and disposal required
Biological treatment (in-situ)	Relatively inexpensive; may not require utilities; can be constructed without obtrusive surface structures	Slow rate of treatment
Chemical oxidation (in-situ)	No air emissions; no secondary waste; VOCs destroyed; can be applied without obtrusive surface structures	May not be cost effective for high contaminant concentrations; requires chemicals such as O_3 or H_2O_2 .
Metal-enhanced dechlorination technology (in-situ)	Dechlorinates chlorinated VOCs to less hazardous substances; generates no air emissions and no secondary waste; no chemicals (such as O_3 or H_2O_2) required; minimal maintenance required; operates passively; no utilities required; in-situ systems can be constructed without obtrusive surface structures	Inability to treat some VOCs ; potential for gradual loss of hydraulic conductivity and reactivity of iron; potential for formation of by-products; construction requires displacement and management of potentially contaminated subsurface soils; geologic conditions may preclude its use at some sites

1.5 Overview of the In-Situ, Metal-Enhanced Dechlorination Technology SITE Demonstration

This section provides an overview of the site, predemonstration and postdemonstration activities, and SITE Program demonstration objectives and procedures.

1.5.1 Site Background

The SITE Program demonstration of the in-situ metal-enhanced dechlorination process was conducted over a 6-month period from June through December 1995. The demonstration took place at an inactive manufacturing facility in central New York state. Former operations at the facility included electroplating and metal finishing (Stearns and Wheler [S&w] 1993).

The site is located in a river valley and overlies unconsolidated materials consisting of a clayey sand and gravel water-bearing zone overlying a dense clay confining layer. The top of the clay layer is about 13 to 16 feet below ground surface. The depth to groundwater varies seasonally, but typically ranges from about 3 to 7 feet below ground surface. The predominant groundwater flow direction on site is west (S&W 1993).

Past site operations appear to have resulted in groundwater contamination in the sand and gravel aquifer. Groundwater samples indicated the presence of a chlorinated VOC plume, apparently related to the electroplating and metal finishing operations, in the west-central part of the site, that was migrating off site to the west. Groundwater contaminants at the site reportedly include the chlorinated VOCs TCE, cDCE, VC, TCA, and 1,1-dichloroethane (DCA); and other compounds (S&W 1993).

Based on the types and concentrations of contaminants in groundwater, the hydrogeologic conditions, and the need to construct a remediation system that would not restrict property use, the metal-enhanced dechlorination process appeared suited for groundwater remediation at the New York site. The system would be used to passively treat groundwater flowing off site to the west, inhibiting off-site migration of chlorinated VOCs (S&W 1994).

1.5.2 Technology Design

In 1994, ETI conducted bench-scale column tests using contaminated groundwater from the New York site.

During these studies, ETI determined the apparent half-lives for chlorinated VOCs present in the site groundwater samples, and for the by-products that could potentially be generated by dechlorinating these VOCs. The half-life data were evaluated to determine the required residence time in the reactive iron for complete dechlorination to occur. The residence time estimates, along with site hydrogeologic characteristics such as hydraulic gradient and flow velocity, determined the required thickness for the reactive iron wall (ETI 1994).

ETI and S&W used the results of the bench-scale studies to custom-design a pilot-scale funnel and gate system. The design contaminant concentrations and applicable regulatory target levels are shown in Table 1-3. The design was based on the estimated residence time required to dechlorinate TCE, cDCE, VC, PCE, and TCA from the influent design concentrations to below the applicable regulatory standards shown on Table 1-3. This time was estimated by ETI as about 56 hours. The system design allowed a minimum residence time of approximately 72 hours for water in the reactive iron based on a predicted maximum groundwater flow velocity of about 1 foot per day through the iron. ETI estimated the groundwater flow velocity based on an assumed horizontal gradient of 0.002, and hydraulic conductivity and porosity values of 142 feet/day and 0.4, respectively, for the iron (ETI 1994).

1.5.3 Technology and Monitoring System Construction

The pilot-scale funnel and gate system was constructed in May 1995. The system was constructed in an agricultural field adjacent to the west side of the site. Figure 1-1 shows the treatment system area layout; Figure 1-2 shows the system configuration in plan view and cross-section.

The system was constructed by driving sealable-joint sheet piling downward from the ground surface, through the sand and gravel, and about 1 foot into the underlying clay layer located about 15 feet below ground surface. The sheet piling formed a rectangular box-like area approximately 12 feet by 6.5 feet in plan. The long dimension of this "box" was perpendicular to the groundwater flow direction. Fifteen-foot-wide sections of sheet piling were also driven on each end of the box. These flanking sections of piling extended about 1 foot down into the clay layer, creating an impermeable barrier to groundwater flow (the funnel) on either end of the box.

Table 1-3. System Design Criteria and Applicable Effluent Standards

Contaminant	Design Influent Concentration ^a (µg/L)	NYSDEC Groundwater Standard (µg/L)	Federal Maximum Contaminant Level (µg/L)
TCA	96	5	200
PCE ^b	90	5	5
TCE	529	5	5
cDCE	5,650	5	70
tDCE	-- ^c	5	100
v c	220	2	2

Source: PRC 1995

Notes:

- ^a Determined by NYSDEC.
- ^b Included as a design parameter and critical parameter for the demonstration; however, PCE was not detected during the SITE demonstration.
- ^c NYSDEC did not require specification of a design **influent** concentration for **tDCE** as **tDCE** was not anticipated to be present at significant concentrations in the **influent** groundwater.

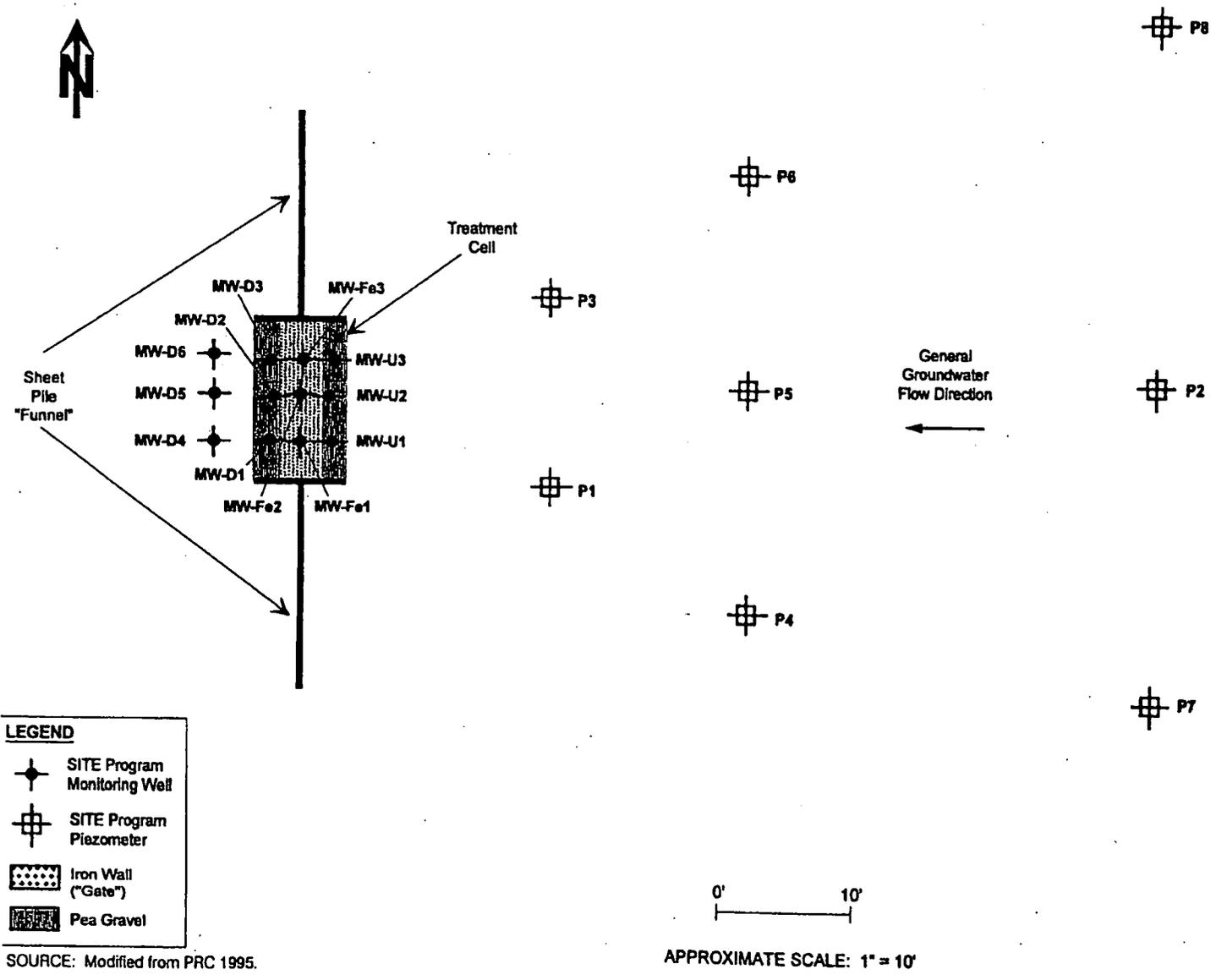


Figure 1-1. SITE demonstration area layout.

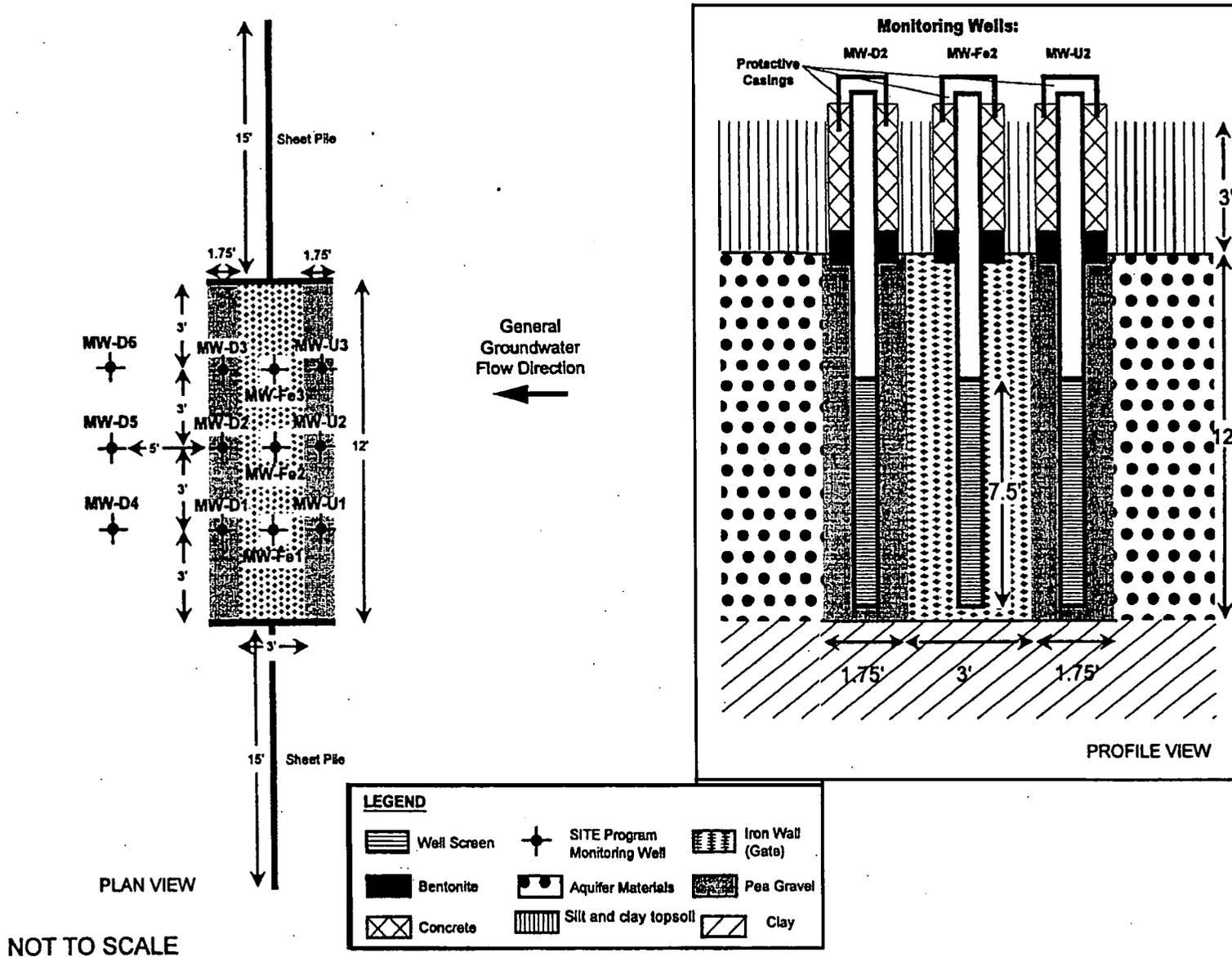


Figure 1-2. Plan and profile views of funnel and gate.

Soil in the area enclosed by the box was then excavated to the top of the clay layer. Soil from the saturated zone was placed in lined roll-off boxes and stored pending analysis and off-site disposal. The box was then dewatered, and sheet piling was used to divide the box into three parallel compartments. The middle compartment, which was 3 feet wide, was backfilled with reactive iron. The compartments on the east (upgradient) and west (downgradient) sides of the iron (each about 1.75 feet wide) were backfilled with pea gravel to minimize the effects of inconsistent flow caused by heterogeneity and anisotropy in the aquifer materials, and to facilitate monitoring well construction. The pea gravel zones and the iron zone are collectively referred to as the "treatment system" or "cell" in subsequent discussions. To differentiate, when referred to specifically, the reactive iron zone is referred to as the "iron wall" throughout subsequent sections. The iron and pea gravel zones were filled to about 3 feet below grade, to allow for a seasonal high groundwater table.

Three groundwater monitoring wells, consisting of PVC well screens with riser pipes attached, were constructed in each compartment. The three monitoring wells in the upgradient pea gravel section were identified as MW-U1, MW-U2, and MW-U3. The wells in the iron were identified MW-Fe1, MW-Fe2, and MW-Fe3; the wells in the downgradient pea gravel section were identified as MW-D1, MW-D2, and MW-D3.

After the monitoring wells were in place and as the compartments were backfilled, the sheet piling dividers between the compartments, as well as the sheet piling forming the long, outer walls of the box (the two sections perpendicular to the groundwater flow direction) were removed. This allowed groundwater to enter the treatment cell, passing in turn through the upgradient pea gravel, reactive iron, and downgradient pea gravel, and then exit the cell and return to the natural aquifer materials. After the sheet piling dividers were removed, the upper 3-foot portion of the trench was backfilled to grade with native topsoil.

In order to provide additional information regarding inorganic analyte concentrations downgradient from the treatment system, three monitoring wells (MW-D4, D5, and D6) were installed about 5 feet downgradient from the treatment system, as shown on Figure 1-1. Eight piezometers (P-1 through P-8) were installed upgradient from the treatment cell to evaluate the hydraulic gradient

and groundwater flow velocity in the vicinity of the system.

1.5.4 Treatment System Operation

Flow through the cell commenced on May 18, 1995. The in-situ system passively treated contaminated groundwater as it flowed through the reactive iron. No additional construction or O&M activities directly related to the metal-enhanced dechlorination process were required. Based on data from upgradient monitoring wells MW-U1, U2 and U3, the **influent** groundwater consistently contained TCE at concentrations ranging from 32 to 330 micrograms per liter ($\mu\text{g/L}$); **cDCE** at concentrations ranging from 98 to 550 $\mu\text{g/L}$; VC at concentrations ranging from about 5 to 79 $\mu\text{g/L}$; and low levels (2 to 12 $\mu\text{g/L}$) of TCA. Trace levels (less than 5 $\mu\text{g/L}$) of 1,1-dichloroethane (DCA) and **tDCE** were also sporadically detected in the **influent** groundwater (see Tables C1 through C6 in Appendix C).

Piezometric data gathered during the SITE demonstration were inconclusive due to the low horizontal flow gradient, but suggested that the groundwater flow velocity through the iron wall was in the range of about 0.4 to 1 foot per day (see Section 2.1.7). Based on these estimates, and an assumed average saturated thickness of 10 feet, the cumulative volume of groundwater treated between the time of construction (May 1995) and the time the demonstration was completed (December 1995) was in the range of about 29,000 to 73,000 gallons.

1.5.5 SITE Demonstration Objectives

EPA and PRC established primary and secondary objectives for the SITE demonstration of the metal-enhanced dechlorination process. The objectives were based on EPA's and PRC's understanding of the metal-enhanced dechlorination process, SITE demonstration program goals, and input from ETI. Primary objectives were considered to be critical for the technology evaluation, while secondary objectives involved collecting additional data considered useful, but not critical, to the process evaluation. The demonstration objectives were defined in the EPA-approved QAPP dated May 1995 (PRC 1995). (A copy of the QAPP accompanies the TER.)

Primary Objectives

The following were the primary (P) objectives of the technology demonstration:

- P1 - Determine whether treated groundwater from ETI's in-situ, permeable treatment wall meets NYSDEC groundwater standards and federal maximum contaminant level (MCL) standards for the critical contaminants: PCE, TCE, TCA, cDCE, tDCE, and VC.
- P2 - Determine the removal efficiency of critical contaminants from groundwater

Primary objective P 1 was established to directly evaluate the metal-enhanced dechlorination process's ability to destroy certain chlorinated VOCs present in groundwater at the New York site, and was to be evaluated based on VOC concentration data from downgradient wells MW-D 1, D2, and D3. Primary objective P-2 was established to provide a quantitative criterion for evaluating system performance, and to provide a basis for comparing the technology's performance with conventional remediation technologies. Objective P-2 was to be based primarily on comparison of upgradient (influent) samples from wells MW-U 1, U2, and U3 to downgradient (effluent) samples from wells MW-D1, D2, and D3.

Secondary Objectives

The following were the secondary (S) objectives of the demonstration:

- S1 - Determine concentration gradients of critical contaminants as groundwater passes through the in-situ treatment wall
- S2 - Examine total metals, chloride, sulfate, nitrate, bicarbonate, and noncritical VOC concentrations in groundwater as it passes through the treatment wall
- S3 - Document geochemical conditions in groundwater as groundwater passes through the treatment wall
- S4 - Examine biological microorganism growth in the reactive iron medium and in upgradient and downgradient groundwater

- S5 - Document operating and design parameters of the in-situ, permeable treatment wall

Secondary objective S1 was to be evaluated based on data from all nine wells in the treatment cell. Objectives S2 and S3 were to be evaluated by comparison of data from all nine wells in the treatment cell (and the three downgradient wells in the aquifer for some parameters), thus providing data on the performance of the reactor, the dechlorination reaction mechanism, and changes in treated groundwater chemistry. Objective S4, which would also be evaluated based on data from the 12 monitoring wells, was established to demonstrate that the metal-enhanced dechlorination process is abiotic, and also to evaluate the potential effect of bacterial growth on the reactive iron. Objective S5 was established to provide data for estimating costs associated with use of the in-situ metal-enhanced dechlorination process, and was to be based on observations during construction, demonstration data, postdemonstration data (if feasible), and data to be provided by S&W and ETI. (Table 2-1 in Section 2 summarizes the demonstration objectives and purposes and the evaluation criteria for each objective, as well as key demonstration findings with respect to each objective.)

1.5.6 Demonstration Procedures

The SITE Program evaluated the treatment system's effectiveness over a period of about 6 months by collecting independent data. In general, three types of data were obtained: 1) analytical data for groundwater samples collected from monitoring wells located in and adjacent to the reactive iron wall; 2) construction and design data and observations, such as bulk density of the iron and geologic conditions; and 3) piezometric data from the 12 monitoring wells and eight piezometers. Data collection procedures for the demonstration were specified in the EPA-approved QAPP written specifically for the in-situ metal-enhanced dechlorination technology demonstration (PRC 1995). Detailed discussions of the sample collection techniques, analytical methods, and deviations from the QAPP are discussed in detail in the TER, which is available from the EPA project manager (see Section 1.7).

Prior to the demonstration, SITE Program personnel observed the construction of the treatment cell and collected samples of the reactive iron medium. The SITE team laboratory analyzed the iron samples to determine the bulk density of the reactive iron medium. SITE Program

personnel also oversaw the installation of eight piezometers (P-1, P-2, P-3, P-4, P-5, P-6, P-7, and P-8) upgradient of the reactive cell and three groundwater monitoring wells downgradient from the cell (see Figure 1-1).

During the demonstration, SITE Program personnel collected groundwater samples from the monitoring wells in and downgradient from the treatment cell, as specified by the QAPP. The first round of sampling was conducted in June, about 2 weeks after installation of the treatment cell and completion of monitoring well development. Subsequent sampling events occurred in July, August, October, November, and December 1995.

During each sampling event, sample fractions for VOC, bicarbonate alkalinity, chloride, sulfate, nitrite nitrogen, and total nitrate/nitrite nitrogen analysis were collected from the nine wells in the treatment cell. SITE Program personnel also collected groundwater sample fractions for metals analysis from the nine wells in the cell and the three downgradient wells located outside of the cell. Sample fractions were collected from all 12 wells for phospholipid fatty acid (PLFA) analysis during June, October, and December. SITE Program personnel also prepared and submitted QA/QC samples as specified in the EPA-approved QAPP (PRC 1995). Samples were shipped to off-site laboratories for analysis.

In addition to the water samples collected for laboratory analyses, SITE Program personnel collected samples for field measurements of dissolved oxygen (DO), temperature, specific conductance, pH, and Eh. Also, field personnel measured the depth to water in the monitoring wells and piezometers to determine the elevation of the piezometric surface and evaluate the hydraulic gradient in the vicinity of the treatment system.

The first sampling event (June 6 through 8) was performed after at least two pore volumes of groundwater had passed through the reactive iron, assuming a minimum flow velocity of about 0.4 foot per day (see Section 2.1.7). One pore volume equals the volume of saturated pore space of the reactive iron medium and is estimated by the developer as about 40 to 45 percent of the total volume of the reactive iron medium, or about 1,200 gallons in this case. However, based on subsequent inspection of the June data, a sufficient amount of water had not yet passed through the system before the June sampling event to allow the downgradient wells (MW-D1 through D-6) to accurately

represent treated groundwater conditions. For this reason, the usefulness of the June data is limited (see Section 2.1).

1.6 Postdemonstration Activities

Interpretation of data gathered from the piezometers during the SITE demonstration regarding groundwater flow velocity was complicated by several factors (see Section 2.1.7). For this reason, approximately 6 months after the SITE demonstration was completed, personnel from ETI and S&W performed a bromide tracer study to provide a more accurate determination of the groundwater flow velocity and the residence time in the reactive iron. ETI subsequently performed another study in November 1996 using a downhole flow meter to attempt to confirm the groundwater flow velocity. These studies were not performed under the supervision of the SITE Program; for this reason, the test procedures are not discussed in detail in this ITER. However, ETI's results are discussed in Section 2.1.7.

1.7 Key Contacts

Additional information on the metal-enhanced dechlorination process, ETI, the SITE Program, and the New York demonstration site is available from the following sources:

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Section 2

Technology Effectiveness Analysis

This section addresses the effectiveness of the metal-enhanced dechlorination technology for treating groundwater contaminated with chlorinated VOCs. This evaluation of the technology's effectiveness is based mainly on the demonstration results supplemented by additional performance data from other applications of this technology and postdemonstration data obtained by ETI.

Vendor claims regarding the effectiveness of the metal-enhanced dechlorination technology are presented in Appendix A. Case studies that describe other applications of the metal-enhanced dechlorination technology are presented in Appendix B. Tables summarizing the laboratory analytical data for groundwater samples collected during the demonstration are included in Appendix C.

2.1 SITE Demonstration Results

This section summarizes the results from the SITE demonstration of the metal-enhanced dechlorination technology for both critical and noncritical parameters, and is organized according to the project objectives stated in Section 1.5.5. Sections 2.1.1 and 2.1.2 address the primary objectives, and Sections 2.1.3 through 2.1.7 address secondary objectives. Table 2-1 summarizes the key demonstration results with respect to the project objectives and summarizes the evaluation criteria for each objective.

The analytical data for samples collected from downgradient wells MW-D1, D2, and D3 in June (about 2 weeks after the treatment wall was constructed) were inconsistent with data collected from the same wells in subsequent months, and do not appear to be representative of actual treated effluent concentrations. For example, as shown in Table C-1 in Appendix C, the average cDCE

concentration in wells MW-D1, D2, and D3 in June was 30.7 µg/L; however, as shown in Tables C-2 through C-6, the cDCE concentration in these wells in subsequent months ranged from about 1.6 to 7.5 µg/L. The treatment cell was dewatered during construction; when the sheet piling was first removed from the upgradient and downgradient sides of the cell groundwater flowed back into the cell from both the upgradient and downgradient sides. The June analytical data appear to indicate that a sufficient quantity of water had not yet passed through the wall to completely flush residual, untreated water from the downgradient pea gravel zone. For this reason, the June data were not used to determine average concentrations and are not discussed in detail for most parameters.

Critical VOCs consistently detected in the influent groundwater during the demonstration were TCE, cDCE, VC, and TCA. TCE was consistently detected in all of the upgradient wells at concentrations ranging from 32 to 330 µg/L; concentrations of cDCE ranged from 98 to 550 µg/L, and concentrations of VC ranged from 4.7 to 79 µg/L. TCA was detected in one or more upgradient wells during all months of testing at relatively low concentrations (3.3 to 13 µg/L). Trace concentrations of tDCE (1.2 to 2.2 µg/L) were detected in one or more upgradient wells during all months except December. PCE was not detected in any of the groundwater samples.

The average concentrations of all critical parameter VOCs (with the exception of PCE) were determined for the influent (upgradient) and effluent (downgradient) groundwater samples. The average values, as well as the individual, monthly data for each parameter, were compared to target levels to support objective P1, and were used to calculate the system removal efficiency (RE) values to support objective P2. More detailed information regarding data interpretation methods is presented in the QAPP and in the TER.

Table 2-1. Demonstration Results with Respect to Objectives

Objective	Description/Purpose	Evaluation Criteria	Results
P1	Determine if the technology achieves target levels for critical VOCs (PCE, TCE, cDCE, tDCE, TCA, and VC)	VOC concentration data from downgradient (effluent) wells MW-D1, D2, and D3 for the period after system performance became relatively stable (July through December 1995)	Average effluent concentrations were all below target levels; four cDCE results out of 15 measurements slightly exceeded target levels; in all cases effluent concentrations were significantly lower than influent concentrations
P2	Determine removal efficiency for critical VOCs	Comparison of VOC data (July through December 1995) from upgradient wells MW-U1, U2, and U3 to data from downgradient (effluent) wells MW-D1, D2, and D3	High removal efficiency for critical VOCs present at significant concentrations in the influent (TCE, cDCE, and VC); no apparent decrease in removal efficiency over demonstration period
S1	Determine concentration gradients of critical VOCs	Comparison of VOC data from upgradient (MW-UI, U2, U3), iron (MW-Fel, Fe2, Fe3), and downgradient (MW-D1, D2, D3) monitoring wells	Most critical VOCs were nondetectable in the iron wells, indicating that the iron wall was thick enough to allow sufficient residence time for dechlorination; also, no measurable increase in typical dechlorination by-products as groundwater passed through the system
s2	Evaluate changes in inorganic and noncritical VOC concentrations as groundwater moves through treatment cell	Comparison of inorganic and noncritical VOC data from same wells as objective S1, plus three wells outside (downgradient) of treatment cell (MW-D4, D5, D6) (metals only)	Bicarbonate alkalinity, calcium, and several other inorganic parameters decreased as water moved through the system, indicating precipitation of metal compounds; one noncritical VOC (DCA) was detected at low concentrations in the influent, and was not detected in the iron wells or downgradient wells
s3	Document geochemical conditions as groundwater moves through treatment cell	Comparison of field parameter results from same wells as S2	Increases in pH and decreases in Eh and conductivity were observed during all months, suggesting conditions were conducive to metal precipitation
s4	Examine biological microorganism growth in the wall	Comparison of phospholipid fatty acid data from same wells as S3	Data do not indicate significant biological activity in iron
S5	Document operating and design parameters	Groundwater flow velocity (piezometric data from all monitoring wells plus piezometers P-1 through P-8); construction observations; bulk density analysis of iron	About 430 cubic feet of iron used; uncompacted bulk density measured at 140 pounds per cubic foot; low horizontal gradient indicated possible slower groundwater flow velocity and longer residence time in iron than anticipated

Notes: P - Primary Objective

S- Secondary Objective

Table 2-2. Summary of Critical VOC Concentrations at Effluent Sampling Locations

VOC	Concentration Detected During Month									Overall Mean Effluent Value ³	Target Effluent Levels	
	June ²			July			August				MCL ⁴	NYSDEC ⁵
	MW-D1	MW-D2	MW-D3	MW-D1	MW-D2	MW-D3	MW-D1	MW-D2	MW-D3			
TCA	4.0	cl.0	<1.0	<1.0	4.0	4.0	4.0	4.0	<1.0	<1.0	200	5
PCE	4.0	4.0	4.0	4.0	<1.0	4.0	cl.0	<1.0	4.0	<1.0	5	5
TCE	<u>5.7</u>	<u>7.3</u>	<u>6.8</u>	4.0	4.0	4.0	3.3	4.0	4.0	cl.3	5	5
cDCE	<u>24</u>	<u>38</u>	<u>30</u>	2.2	3.7	3.9	<u>6</u>	1.6	1.9	3.9	70	5
tDCE	4.0	<1.0	4.0	<1.0	4.0	4.0	4.0	4.0	4.0	cl.0	100	5
VC	1.3	<u>2.1</u>	1.6	4.0	4.0	<1.0	<1.0	<1.0	4.0	<1.0	2	2

VOC	Concentration Detected During Month									Range of Effluent Values ³	Overall Mean Effluent Value ³	Target Effluent Levels:	
	October			November			December					MCL ⁴	NYSDEC ⁵
	MW-D1	MW-DP	MW-D3	MW-D1	MW-DP	MW-D3	MW-D1	MW-D2	MW-D3				
TCA	4.0	4.0	<1.0	4.0	4.0	<1.0	4.0	<1.0	<1.0	All <1.0	4.0	200	5
PCE	4.0	<1.0	<1.0	4.0	4.0	<1.0	4.0	4.0	4.0	All <1.0	4.0	5	5
TCE	1.2	1.5	<1.0	1.6	<1.0	4.0	0.91J	cl.0	4.0	0.91 J - 3.3	<1.3	5	5
cDCE	5	7.5	2	4.6	4.2	2.8	2.5	<u>5.6</u>	<u>5.4</u>	1.6-7.5	3.9	70	5
tDCE	4.0	<1.0	<1.0	<1.0	4.0	4.0	4.0	<1.0	4.0	All <1.0	<1.0	100	5
VC	4.0	1.2	<1.0	<1.0	<1.0	<1.0	4.0	<1.0	<1.0	4.0 - 1.2	<1.0	2	2

Notes: All values are presented in micrograms per liter.

For monthly samples, "<" (less than) symbol indicates that a compound was not detected; corresponding value is detection limit and is value used to calculate overall mean.

Overall mean values based on one or more 'nondetects' are also reported as "<" (less than) corresponding value.

Values exceeding at least one applicable target effluent standard are shown underlined.

J = Value estimated; concentration detected is below minimum quantitation limit.

¹ 1,1,1-trichloroethane (TCA); tetrachloroethene (PCE); trichloroethene (TCE); cis-1,2-dichloroethene (cDCE); trans-1,2-dichloroethene (tDCE); and vinyl chloride (VC).

² June data were collected before representative effluent (downgradient) conditions were attained, and are not used to determine average values.

³ Value based on data collected from wells MW-D1, D2, and D3 from July through December.

⁴ MCL = federal maximum contaminant level.

⁵ NYSDEC = New York State Department of Environmental Conservation groundwater discharge standard.

2.1.1 Objective P1: Compliance with Applicable Effluent Target Levels

Compliance with the target levels was evaluated by comparing the critical parameter concentrations detected in downgradient wells MW-D1, D2 and D3 during July, August, October, November, and December, and the average value for each contaminant detected in these wells, to federal MCLs and NYSDEC groundwater discharge standards.

The detection limit for all critical parameters in the effluent samples was $1 \mu\text{g/L}$, and most of the samples collected from the downgradient wells during the demonstration did not contain detectable concentrations of critical contaminants, with the exception of **cDCE**, and, less frequently, TCE and VC. Ten out of 15 TCE results for the period from July to December were below detectable limits, as were 13 out of 15 VC results for the same period. Low concentrations of **cDCE** were detected in wells MW-D1, D2, and D3 during each sampling event. All critical VOC concentrations measured in individual wells from July through December were below MCLs. Critical VOC concentrations were also below NYSDEC target levels in most instances (86 out of 90 measurements). Only one contaminant, **cDCE**, slightly and sporadically exceeded the NYSDEC target effluent level of $5 \mu\text{g/L}$ during this period (well MW-D1 during August, well MW-D2 in October, and wells MW-D2 and D3 in December). However, the maximum **cDCE** concentration detected in any of the downgradient samples collected from July to December was relatively low ($7.5 \mu\text{g/L}$) and in all cases was significantly less than the **influent cDCE** concentration detected during the same month.

Overall, concentrations of all critical contaminants, including VOCs such as **cDCE**, **tDCE** and VC, which are potential by-products of the dechlorination of TCE, were significantly lower in downgradient wells than in upgradient wells. For this reason, the VOC data appear to indicate that residence time was sufficient to allow the technology to dechlorinate any by-products generated through the dechlorination of TCE.

2.1.2 Objective P2: Critical Parameter Removal Efficiency

The efficiency with which the in-situ metal-enhanced dechlorination process removed contaminants from

groundwater was evaluated by comparing the average upgradient and average downgradient concentrations of the six critical parameter VOCs: TCA, TCE, PCE, **cDCE**, **tDCE**, and VC. Removal efficiency for each compound was evaluated for each of the five data sets collected after system performance appeared to stabilize (July, August, October, November, and December). Overall system removal efficiency for each compound, based on values averaged for each parameter for the period from July through December, was also calculated. The average upgradient and downgradient critical parameter concentrations for each month, the overall average values and the removal efficiency data are presented in Table 2-3.

In cases where effluent concentrations of a compound were nondetectable, the detection limit value ($1.0 \mu\text{g/L}$), rather than an assumed concentration of $0.0 \mu\text{g/L}$, was used to calculate the minimum removal efficiency. This conservative practice, which was specified by the QAPP, was adopted to ensure that the removal efficiency would not be overestimated, and assumes that a compound not detected in the effluent at a detection limit of $1.0 \mu\text{g/L}$ may have been present at a concentration between $0.0 \mu\text{g/L}$ and $1.0 \mu\text{g/L}$. For this reason, the removal efficiency values in Table 2-3 are the minimum possible values and may be lower than the actual removal efficiencies achieved by the system. For example, as shown in Table 2-3, although VC was not detected in any downgradient wells in August the minimum removal efficiency was not reported as "100 percent." Instead, the removal efficiency for VC was based on an assumed average downgradient concentration of $1.0 \mu\text{g/L}$ and was reported as "greater than 91.1 percent", indicating that the actual value lies in the range between 91.1 percent and 100.0 percent.

The removal efficiency calculations are also influenced by the magnitude of the **influent** concentrations relative to the detection limit value ($1.0 \mu\text{g/L}$) assigned as the effluent concentration for nondetect situations. If low concentrations of a VOC (for example **tDCE** or TCA), were present in the influent, the assigned effluent value of $1.0 \mu\text{g/L}$ was greater in proportion to the **influent** concentration than in cases where higher **influent** concentrations were present (as for **cDCE** or TCE). For this reason, situations involving low **influent** concentrations typically resulted in lower calculated removal efficiency values, even though the contaminant was reduced to nondetectable levels in the effluent.

The results presented in Table 2-3 indicate that removal efficiency was high for all contaminants present at

Table 2-3. Summary of Critical Parameter Removal Efficiency: July-December 1995

v o c	July			August		
	Average Upgradient Concentration (µg/L) ¹	Average Downgradient Concentration (µg/L) ²	Removal Efficiency (%) ³	Average Upgradient Concentration (µg/L) ¹	Average Downgradient Concentration (µg/L) ²	Removal Efficiency (%) ³
TCA	<2.2	<1	>54.5	4.9	<1	>79.5
PCE	<1	<1	NC	<1	<1	NC
TCE	180.0	<1	>99.4	183.3	<1.8	>99.0
cDCE	290.0	3.3	98.9	306.7	3.2	99.0
tDCE	4.1	<1	>9.0	<1.4	<1	>28.5
v c	19.0	<1	>94.7	11.3	<1	>91.1

v o c	October			November		
	Average Upgradient Concentration (µg/L) ¹	Average Downgradient Concentration (µg/L) ²	Removal Efficiency (%) ³	Average Upgradient Concentration (µg/L) ¹	Average Downgradient Concentration (µg/L) ²	Removal Efficiency (%) ³
TCA	7.1	<1	>85.9	4.9	<1	>79.5
PCE	<1	<1	NC	<1	<1	NC
TCE	143.3	<1.3	>99.0	69.0	<1.2	>98.2
cDCE	380.0	4.8	98.7	159.3	3.9	97.6
tDCE	1.8	<1	>44.4	1.3	<1	>23.0
v c	60.3	4.1	>98.1	14.3	<1	>93.0

v o c	December			Overall Minimum Removal Efficiency for Demonstration Period:		
	Average Upgradient Concentration (µg/L) ¹	Average Downgradient Concentration (µg/L) ²	Removal Efficiency (%) ³	Overall Mean Influent Concentration (µg/L) ⁴	Overall Mean Effluent Concentration (µg/L) ⁵	Minimum Removal Efficiency % ⁶
TCA	12.3	<1	>91.8	<6.3	4.0	>84.1
PCE	<1	<1	NC	<1.0	<1.0	NC
TCE	120.0	<1	>99.1	139.1	<1.3	>99.0
cDCE	230.0	4.5	98.0	273.2	3.9	98.6
tDCE	<1	<1	NC	1.3	<1.0	NC
VC	21.7	<1	>95.3	25.3	<1.0	>96.0

Notes:

- <=average value is less than value shown; applies to instances where one or more values used to calculate average were "nondetect" and were assigned the detection limit concentration of 1 µg/L.
- > = indicates that removal efficiency is based on one or more "nondetect" values and is greater than value shown.
- NC= removal efficiency not calculated; contaminant was not consistently detected in influent samples or effluent samples.
- ¹ Monthly average of concentrations detected in upgradient wells MW-U1, U2, and U3
- ² Monthly average of concentrations detected in downgradient wells MW-D1, D2, and D3.
- ³ Monthly removal efficiency = 100 X [(average upgradient concentration - average downgradient concentration) / average upgradient].
- ⁴ Mean of concentrations detected in upgradient wells MW-U1, U2, and U3 from July through December.
- ⁵ Mean of concentrations detected in downgradient wells MW-D1, D2, and D3 from July through December.
- ⁶ Overall minimum removal efficiency (RE) for each parameter is based on data collected from July through December and calculated using the following formula: Minimum RE = 100 X [(Mean Influent Concentration - Mean Effluent Concentration) / Mean Influent Concentration].

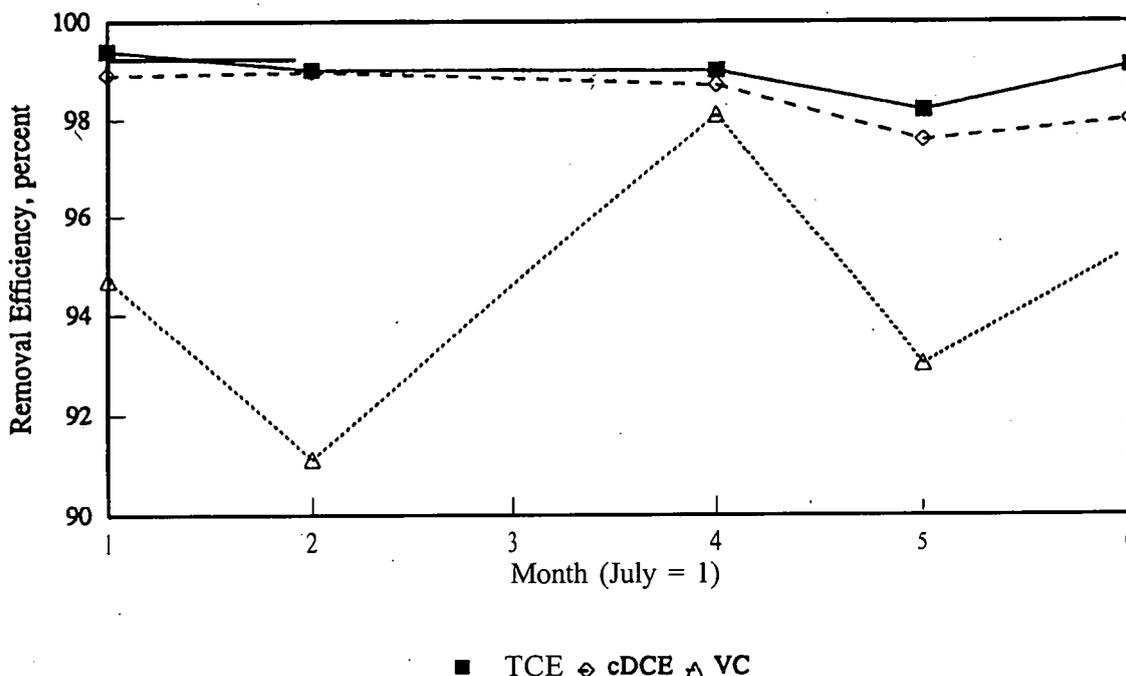
significant concentrations in the **influent** (TCE, **cDCE**, and VC). The minimum monthly removal efficiencies for TCE ranged from greater than 98.2 percent to greater than 99.4 percent, and the overall minimum removal efficiency was greater than 99.0 percent. For **cDCE**, monthly values ranged from 97.6 percent to 99.0 percent, and the overall minimum removal efficiency was 98.6 percent. Monthly removal efficiency values for vinyl chloride ranged from greater than 91.1 percent to greater than 98.1 percent, with overall minimum removal efficiency greater than 96.0 percent. Monthly and overall removal efficiency values were not calculated for PCE because no PCE was detected in the **influent** or effluent samples during any month of testing.

Figure 2-1 shows the calculated minimum monthly removal efficiency values for the critical contaminants present at significant concentrations in the **influent** (TCE, **cDCE**, and VC). As indicated on Figure 2-1, there did not appear to be any significant trends in the monthly system removal efficiency for any of these contaminants from July to December. Figure 2-1 reflects a slight decrease in calculated removal efficiency for these three parameters in November; however, the apparent decrease merely

reflects a decrease in **influent** concentrations. This observation is significant because the results of the inorganic analyses (see Section 2.1.4) suggest that metal compounds were precipitating in the iron as groundwater passed through the system. Precipitates did not noticeably affect system performance with respect to removal efficiency during the period of the SITE demonstration.

2.1.3 Objective S-1: Critical Parameter Concentrations as a Function of Sampling Location (Distance)

Figures 2-2 through 2-7 plot concentrations of critical contaminants relative to distance as groundwater moved through the system. Data from each group of wells (upgradient, iron, and downgradient) were averaged for each month to facilitate presentation of data in Figures 2-2 through 2-7. The three data points on each graph represent the upgradient pea gravel (distance $x=0$ feet; iron ($x=2.4$ feet); and downgradient pea gravel ($x=4.8$ feet). Only those critical contaminants consistently detected in the **influent** samples are plotted in Figures 2-2 through 2-7.



RE calculated for months after performance stabilized (July - December); no data collected in month 3 (September); RE based on average values for upgradient (MW-U1, 2 and 3) and downgradient (MW-D1, 2, and 3) wells.

Figure 2-1. Critical VOC removal efficiency over time.

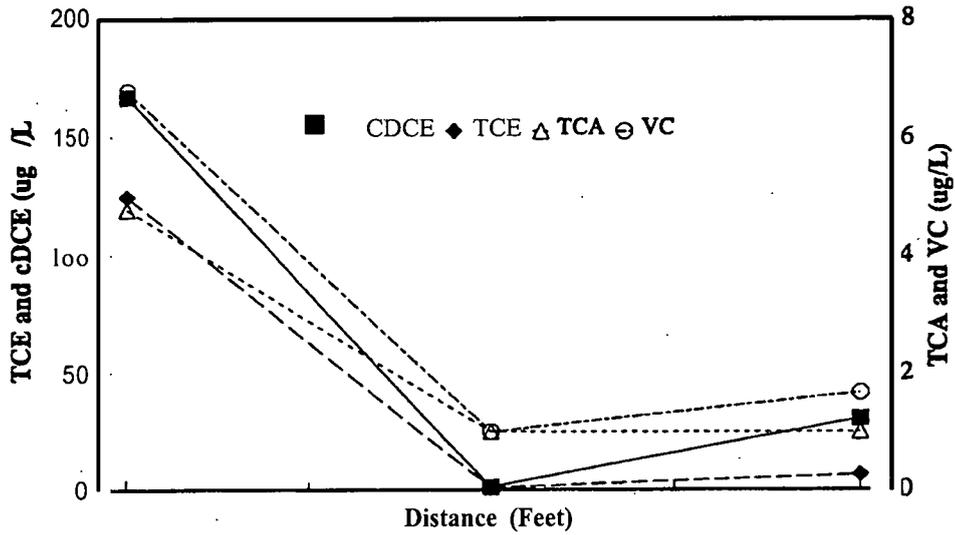
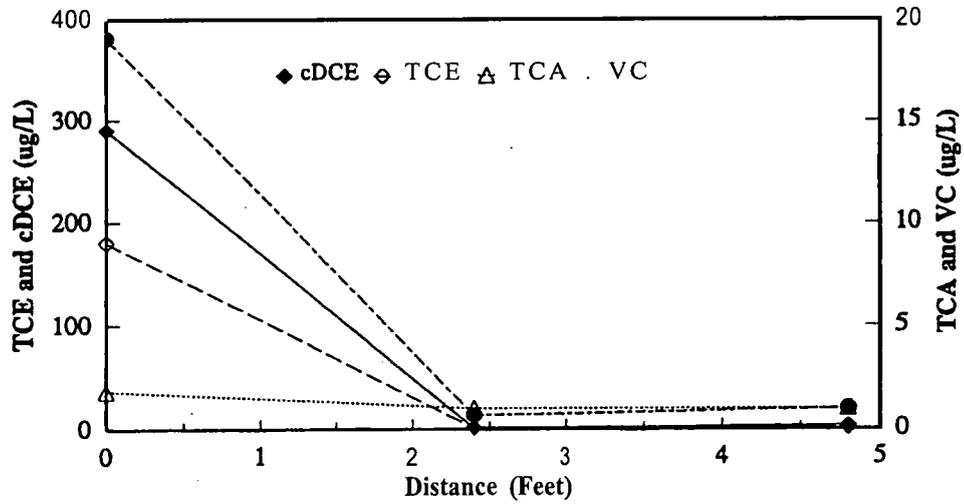


Figure 2-2. Critical VOCs vs. distance-June.



ug/L = micrograms per liter; values are averages for: upgradient pea gravel (X=0 feet); iron (X=2.4 feet); downgradient pea gravel (X=4.8 feet); non-detect values plotted as detection limit (1 ug/L).

Figure 2-3. Critical VOCs vs. distance-July.

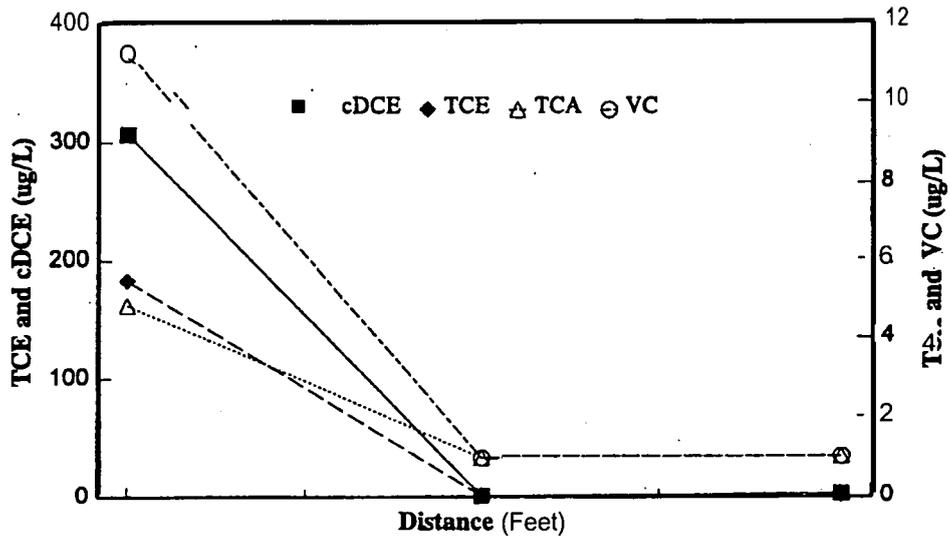
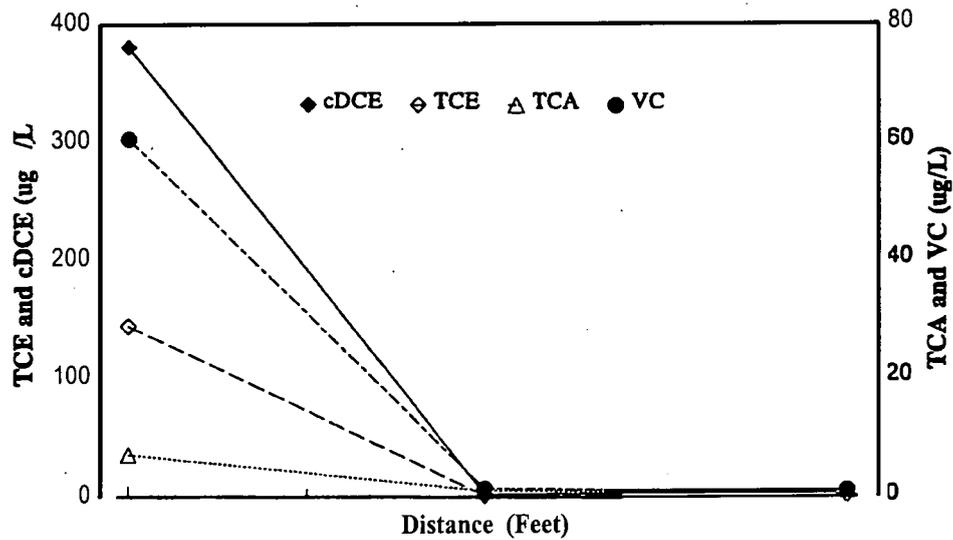


Figure 2-4. Critical VOCs vs. distance-August.



ug/L = micrograms per liter; values are averages for: upgradient pea gravel (X = 0 ft); iron (X = 2.4 feet) and downgradient pea gravel (X = 4.8 feet); non-detect values plotted as detection limit (1 ug/L).

Figure 2-5. Critical VOCs vs. distance-October.

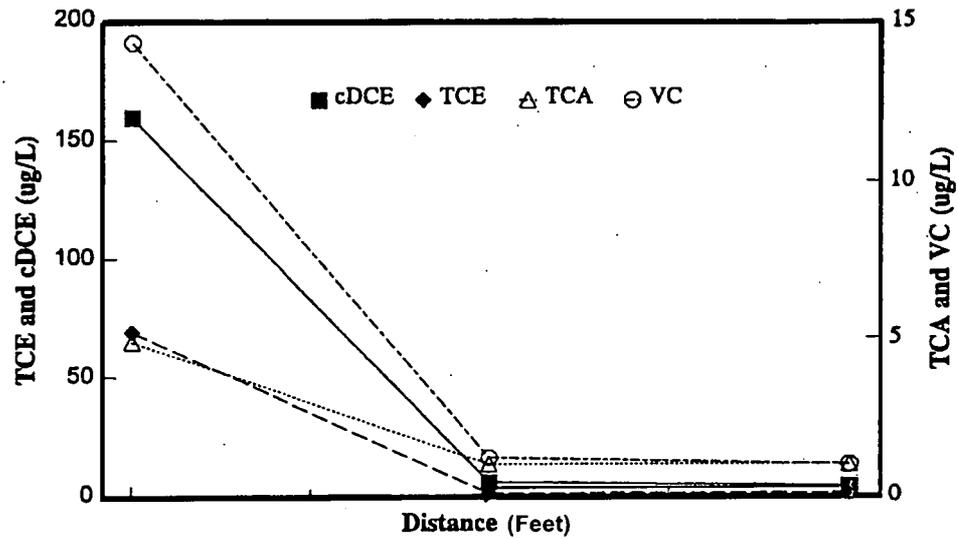
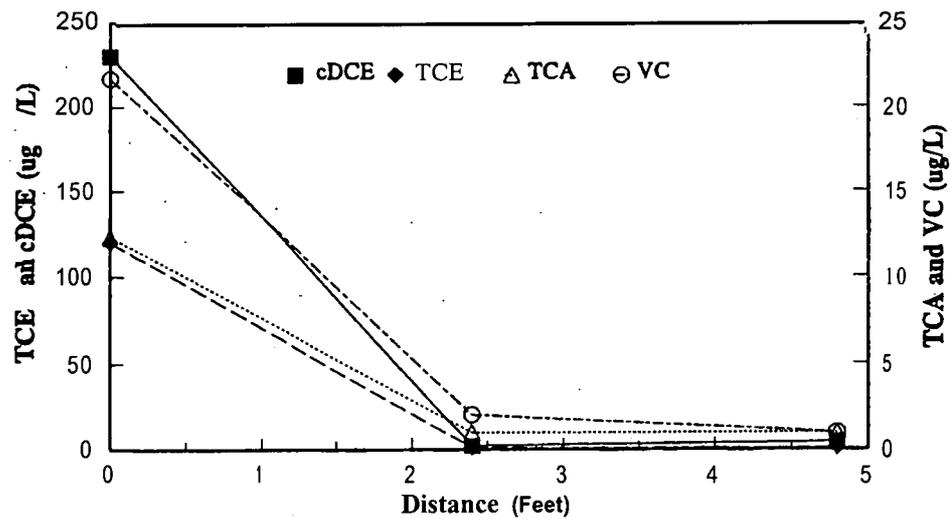


Figure 2-6. Critical VOCs vs. distance-November.



ug/L=micrograms per liter; values are averaged for: upgradient pea gravel (x=0 feet); iron (X=2.4 feet); and downgradient pea gravel (x=4.8 feet). Nondetect values plotted as detection limit (1 ug/L).

Figure 2-7. Critical VOCs vs. distance-December.

Concentrations of critical parameters present at significant concentrations in the **influent** (TCE, **cDCE**, and VC) were significantly reduced as groundwater moved through the wall. As shown in Figures 2-2 through 2-7, in most cases, contaminants were reduced to nondetectable levels by the time groundwater had traveled about halfway through the iron wall. Some low concentrations of **cDCE** appeared to persist; however, during all months **cDCE** was significantly reduced relative to **influent** concentrations. In several instances (for example, TCE in October), all concentrations in the iron wells were at nondetectable levels; however, trace concentrations appeared in the downgradient wells. The presence of low concentrations of TCE, **cDCE**, and other compounds in the downgradient wells may have been caused by residual **VOCs** in the natural aquifer materials on the downgradient side of the cell continuing to leach minor amounts of chlorinated **VOCs** into groundwater, and some of this water mixing with treated water in the downgradient pea gravel zone.

The results of a previous demonstration of an aboveground application of the metal-enhanced dechlorination process indicated that chlorinated **VOCs** were persisting for longer periods (greater distances) in the iron as the demonstration progressed, possibly due in part to precipitate formation (EPA 1997). However, for the in-situ system, the **VOC** data do not appear to exhibit significant trends indicative of changes in the iron's ability to dechlorinate the critical contaminants. Critical **VOC** concentrations in monitoring wells MW-Fe1, MW-Fe2, and MW-Fe3, which were located approximately halfway through the reactive iron wall (in the direction of groundwater flow) did not increase significantly during the demonstration period. Although the results of the inorganic analyses suggest that metal compounds were precipitating as groundwater moved through the iron, these precipitates did not cause a noticeable reduction in the iron's performance during the demonstration period. Differences between the performance of the aboveground reactor and that of the in-situ system may have been due to differences between the residence times for groundwater in the two systems; differences in contaminant loading for the two systems; variations between groundwater chemistry at the two demonstration sites, or other factors.

Precipitate formation may have been less significant of a factor in the demonstration of the in-situ system than in the demonstration of the aboveground reactor because the volume of water treated, flow rate, mass of iron used, groundwater chemistry, length of demonstration period,

and other factors differed between the two demonstrations. Also, based on the apparent groundwater flow velocities, the reactive iron wall was probably thicker than necessary to dechlorinate the concentrations of **VOCs** detected in the upgradient wells, and therefore had excess treatment capacity. This factor, and the availability of only one row of measuring points in the reactive iron may have allowed changes in the first few inches of iron on the upgradient side of the wall to go undetected during the demonstration period.

In summary, the data indicate two key findings with regard to objective S-1: 1) because most contaminants were reduced to nondetectable levels by the time groundwater had traveled halfway through the reactive iron, the thickness of the reactive iron wall appeared to be more than adequate to allow sufficient residence time for dechlorination to occur; and 2) the dechlorination of TCE and **cDCE** was not causing increased concentrations of potential by-products (**cDCE** and VC) in the downgradient wells, indicating that the iron was dechlorinating all of these compounds.

2.1.4 Objective S-2: Noncritical VOCs, Metals, And Other Inorganic Parameters

Tables C 1 through C6 in Appendix C summarize all of the laboratory analytical data collected during the demonstration, including the results of the noncritical **VOC**, metals, and other inorganic parameter analyses. Specifically, these parameters were analyzed to evaluate effects of the reactive iron on noncritical parameters, and to provide additional data about the dechlorination of **VOCs**, metal precipitation, and the potential for biological growth. Due to the extensive number of analytical parameters and sampling points pertaining to this objective, only results for significant parameters are presented in graphical format.

Noncritical VOCs

The samples were analyzed for a total of 64 **VOCs** on EPA's Target Compound List (TCL); tentatively identified compounds (TICs) were also reported. The only significant noncritical **VOC** consistently detected in the upgradient, influent groundwater was DCA, which was detected at low concentrations (less than 6 µg/L) during all months of testing. DCA was below detectable levels in the

iron wells in all but two cases (MW-Fe3 in November and December), and was below detectable levels in all of the downgradient wells during these months. In all instances, DCA concentrations in the iron wells and downgradient wells were below the applicable NYSDEC and MCL standards, both of which are equal to 5.0 µg/L. This observation is consistent with ETT's past research data, which indicated that the reactive iron is capable of dechlorinating DCA (Focht, Vogan, and O'Hannesin 1996).

As indicated in Table C-2, during July TCE and cDCE were detected in a sample from well MW-D4, and TCE, cDCE, and VC were detected in a sample from well MW-D5. VOC sample fractions were collected from these wells solely to provide information to support the demonstration health and safety program. The QAPP did not specify collection of VOC sample fractions from these wells to support primary or secondary objectives; for this reason, the results are not critical parameters and are not discussed in detail in this report. However, it should be noted that both wells MW-D4 and MW-D5 are located outside of the treatment cell, and the VOC sample fractions were collected relatively early in the demonstration (July). As previously discussed, possible mixing of treated groundwater and residual, untreated water may have resulted in the presence of VOCs in samples from these wells.

Metals

The groundwater samples were analyzed for a total of 16 metals using inductively-coupled plasma (ICP) and atomic absorption (AA) techniques. Data for several of the metals detected appear to indicate trends indicative of precipitate formation. These metals include calcium, magnesium, barium, iron, and manganese.

Figures 2-8 and 2-9 summarize the average calcium and magnesium concentrations in each row of wells (including the downgradient wells screened in the natural aquifer materials) from June through December. Figure 2-10 summarizes the average calcium and magnesium data collected from each row after system performance stabilized (July through December). As shown by the figures, **influent** concentrations of each of these metals exhibited relative consistency among months. During all months, concentrations of calcium generally decreased between the upgradient wells and the iron wells, and then appeared to gradually increase in the downgradient pea

gravel and aquifer wells. The decrease in calcium concentrations coincided with a decrease in bicarbonate alkalinity and an increase in measured pH values, suggesting that geochemical conditions in the iron were conducive to decreased solubility and increased precipitation of calcium carbonate and other metal compounds onto the iron.

Magnesium concentrations also generally decreased between the upgradient pea gravel and reactive iron; however, unlike calcium, magnesium concentrations continued to decrease as groundwater moved through the downgradient pea gravel, and then increased slightly in the downgradient aquifer. This observation suggests that magnesium compounds continued to precipitate as groundwater moved downgradient from the reactive iron zone. The slight increase observed in magnesium concentrations downgradient from the cell may be due to mixing of treated and untreated water downgradient of the cell. Also, samples collected from wells MW-D4, D5 and D6, which were screened in the natural aquifer materials, generally appeared to contain a higher concentration of suspended sediments than samples from wells screened in the pea gravel or iron. These suspended fines may have affected the analyses as the samples were not filtered before analysis.

Iron and manganese concentrations are plotted in Figures 2-11 through 2-13. As evidenced by the figures, the samples from wells in the reactive iron typically contained the highest iron concentrations of the four rows monitored. This is consistent with the nature of the proposed reaction mechanism (see Section 1.3) which suggests that the oxidation of iron and the hydrolysis of water will cause iron compounds such as $\text{Fe}(\text{OH})_2$ and FeCO_3 to form, and then subsequently precipitate out due to the elevated pH levels. In August, November, and December iron concentrations in the downgradient aquifer wells were higher than background concentrations but were still relatively low (less than 1 mg/L). However, during June, July, and October, iron concentrations in the downgradient aquifer wells were below background levels. For this reason, the iron data do not strongly indicate trends regarding the persistence of dissolved iron as groundwater moved downgradient in the aquifer.

Unlike iron, manganese concentrations appeared to decrease between the upgradient pea gravel and reactive iron zones, and then gradually increase in the downgradient wells. The cause for the apparent behavior

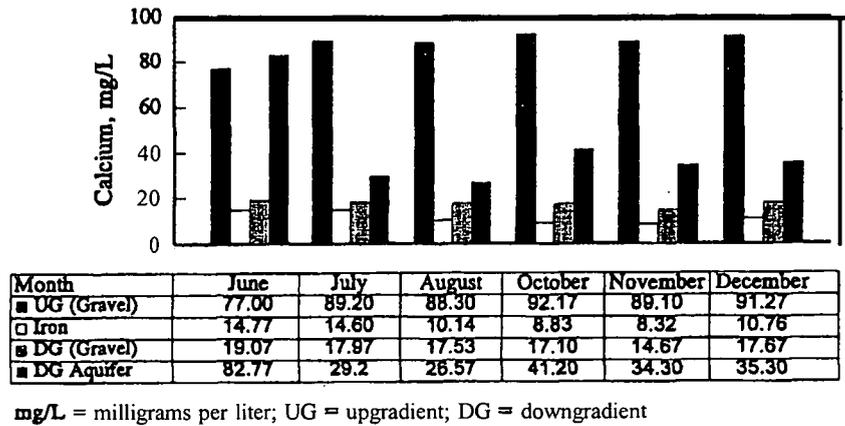


Figure 2-8. Summary of calcium data over time.

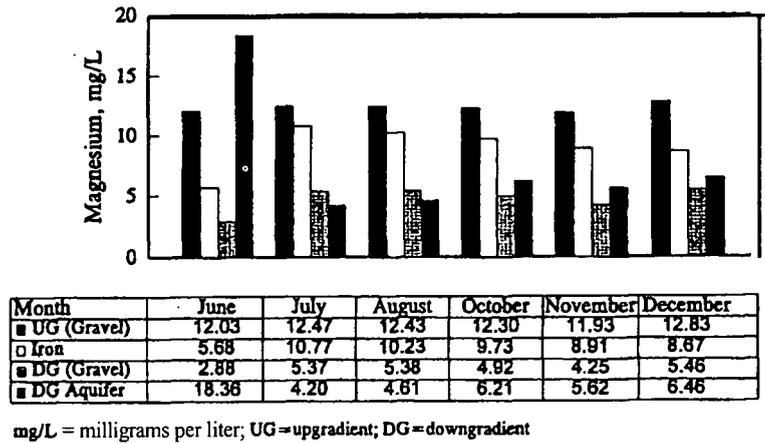
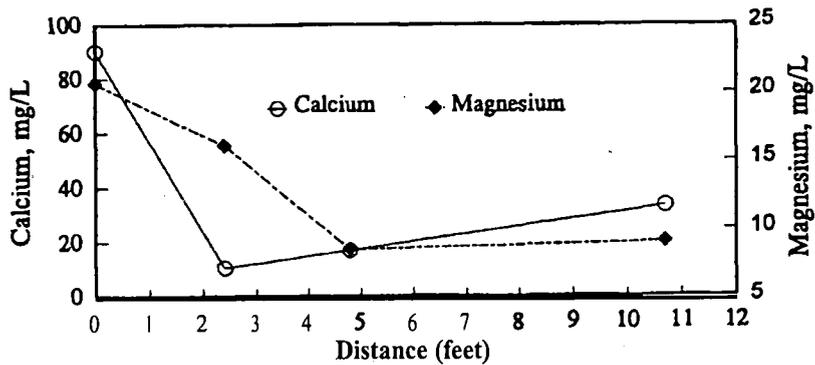
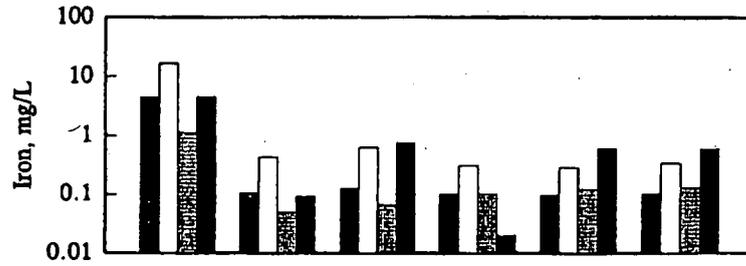


Figure 2-9. Summary of magnesium data over time.



mg/L = milligrams per liter; values based on July-December, averaged for: upgradient (X=0 ft), iron (x=2.4 ft); downgradient (x=4.8 ft), and downgradient aquifer (x= 10.7 ft) wells.

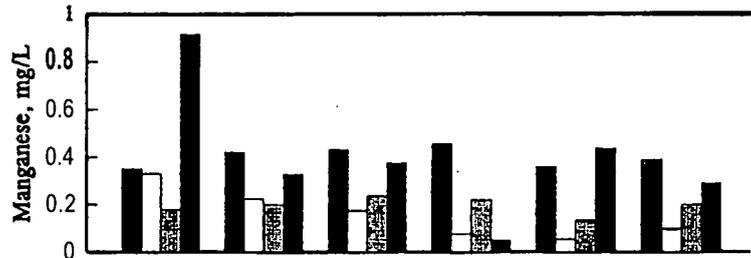
Figure 2-10. Average calcium and magnesium values vs. distance.



Month	June	July	August	October	November	December
■ UG (Gravel)	4.42	0.10	0.12	0.10	0.10	0.10
□ Iron	16.62	0.43	0.63	0.30	0.28	0.33
▨ DG (Gravel)	1.12	0.05	0.07	0.10	0.12	0.13
■ DG Aquifer	4.59	0.09	0.75	0.02	0.60	0.59

mg/L = milligrams per liter; UG = upgradient; DG = downgradient;
all nondetect values plotted as detection limit (0.10 mg/L)

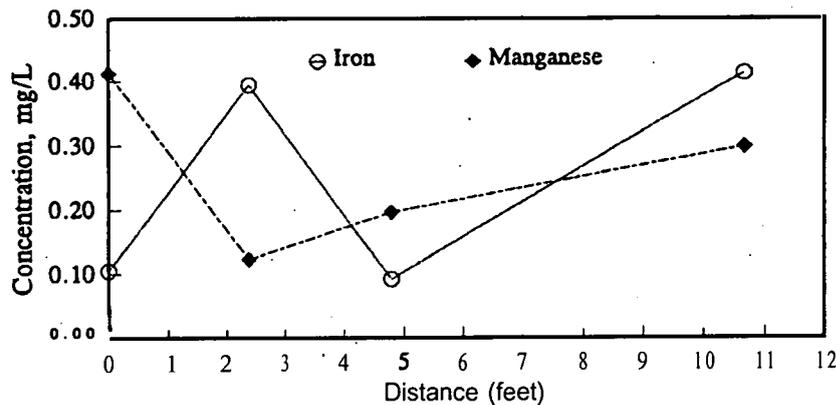
Figure 2-11. Summary of iron data over time.



Month	June	July	August	October	November	December
■ UG Gravel	0.35	0.42	0.43	0.46	0.36	0.39
□ Iron	0.33	0.22	0.17	0.07	0.05	0.09
▨ DG Gravel	0.18	0.20	0.23	0.22	0.13	0.20
■ DG Aquifer	0.91	0.33	0.38	0.05	0.44	0.29

mg/L = milligrams per liter; UG = upgradient; DG = downgradient;

Figure 2-12. Summary of manganese data over time.



mg/L = milligrams per liter; values based on July-December, averaged for: upgradient (X=0 ft);
iron (X=2.4 ft); downgradient (X=4.8 ft); and downgradient aquifer (X=10.7 ft) wells.

Figure 2-13. Average iron and manganese values vs. distance.

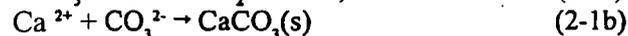
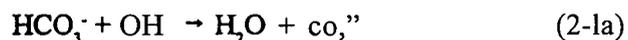
is unknown. According to ETI, this may have been caused by naturally occurring manganese in site groundwater being absorbed into carbonate precipitates forming as groundwater moved through the reactive iron, or other factors (Vogan 1996). Manganese concentrations downgradient of the wall generally appeared to be similar to upgradient concentrations. Overall, it does not appear that the iron wall was introducing more manganese to groundwater than was present at naturally occurring background levels.

As shown in Figure 2- 14, barium concentrations generally increased between the upgradient pea gravel wells and the iron wells, and then declined. However, the magnitude of the increase in barium lessened with each month. The possible cause of this observation is unknown, but may be a residual effect of the cell construction activities that lessened with time as groundwater continued to “flush” the reactive iron. According to ETI, after initial emplacement the iron may have temporarily leached small amounts of barium into groundwater passing through the wall (ETI 1997). However, barium did not appear to be persisting into the downgradient aquifer; barium levels generally decreased between the reactive iron wells and the downgradient wells.

Other Inorganic Parameters

Other inorganic parameters (bicarbonate alkalinity, sulfate, chloride, nitrate, and nitrite) were measured in the upgradient pea gravel, iron, and downgradient pea gravel wells.

Figures 2- 15 and 2- 16 plot the average bicarbonate alkalinity concentrations in the various rows of wells. The results indicate that bicarbonate alkalinity decreased as groundwater moved through the reactive iron wall, coinciding with an increase in pH, and then increased slightly as groundwater moved downgradient. This behavior is consistent with the results of the calcium, magnesium, and pH analyses, which suggested that metal-carbonate compounds were precipitating out. Figure 2- 16 graphically exhibits the relationship between bicarbonate concentrations and pH. According to Reardon (1995), as pH increases, hydroxide (OH⁻) ions react with bicarbonate ions (HCO₃⁻) to form carbonate ions (CO₃²⁻), which then may combine with iron, calcium, magnesium, and other metals to form metal-carbonate precipitates. Equation 2- 1 shows the formation of calcium carbonate through this mechanism:



The slight increase in bicarbonate in the downgradient pea gravel wells is consistent with the slight drop in pH and increase in calcium concentrations observed. These observations indicate that the tendency for metal carbonates to precipitate was decreasing as groundwater passed out of the treatment cell.

As shown in Figure 2-17, **influent** sulfate concentrations were generally consistent over the demonstration period, ranging from about 14 to 20 milligrams per liter (mg/L), and generally appeared to decrease as groundwater moved through the treatment cell during all months. The reduction in sulfate concentrations appeared to be more complete and was occurring more rapidly as the demonstration progressed. For example, in July the average sulfate concentrations in the upgradient, iron, and downgradient wells were 16.8, 15.5, and 10.6 mg/L, respectively. In December the average upgradient concentration was consistent with July (16.6 mg/L); however sulfate was nondetectable in the iron wells and in the downgradient wells.

Sulfate concentrations were measured to evaluate, in part, the potential for sulfate-reducing bacterial growth and precipitation of metal sulfates. According to ETI, sulfate reduction may indicate biological activity in the reactive iron. However, the PLFA analyses did not indicate significant microbial activity in the reactive iron (see Section 2.1.6); therefore, it is unknown if the decrease in sulfate concentrations was due to biological activity or other causes, such as precipitation of metal-sulfate compounds.

Figures 2- 18 and 2-19 exhibit the total nitrate/nitrite nitrogen results. Total nitrate/nitrite and nitrite analyses were performed on the samples from the nine wells in the treatment cell; the total nitrate content was then determined by calculating the difference between the total nitrate/nitrite values and the nitrite values. Total nitrate/nitrite concentrations detected in samples from the upgradient pea gravel wells ranged from about 0.16 to 0.47 mg/L, and gradually decreased during the demonstration. As shown in Tables C-1 through C-6, the analyses indicated that both nitrate and nitrite were present in the **influent** groundwater. The relative proportion of each of these compounds to the total nitrate/nitrite nitrogen

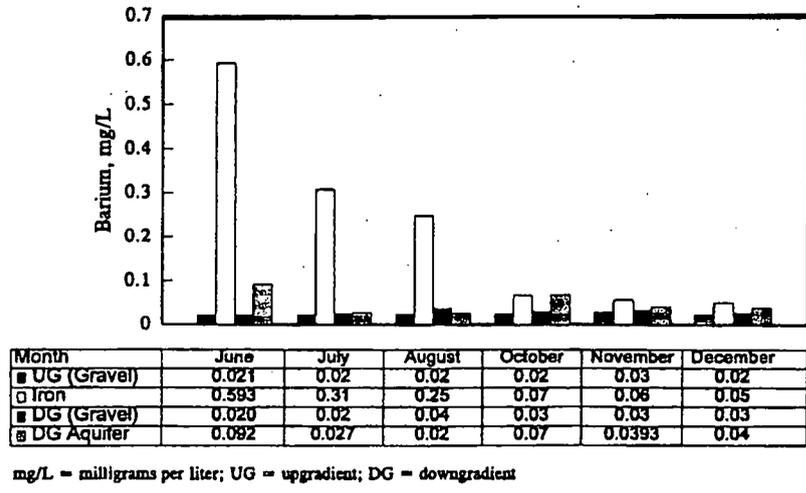


Figure 2-14. Summary of barium data over time.

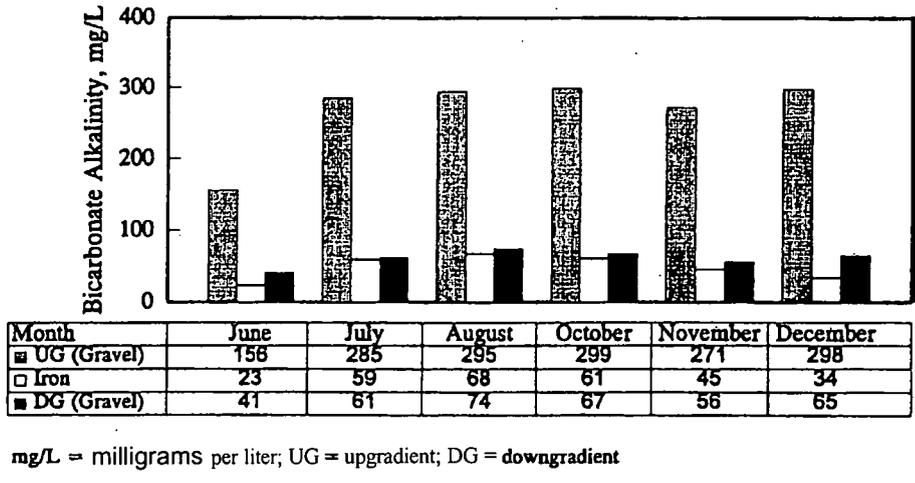
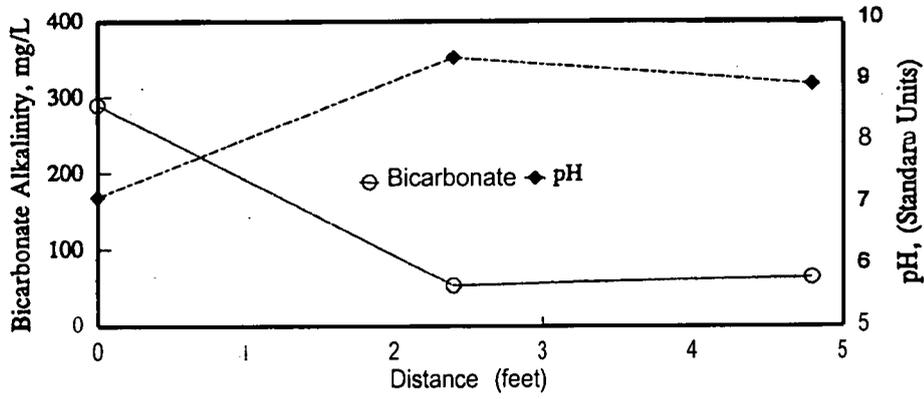
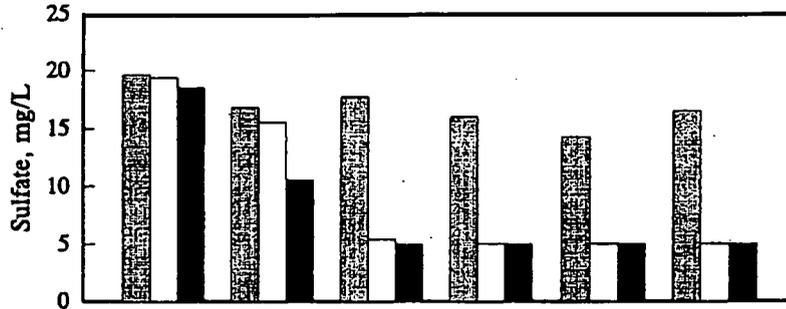


Figure 2-15. Summary of bicarbonate alkalinity data over time.



mg/L = milligrams per liter; values based on data from July-December, averaged for: upgradient (x=0 ft); iron (x=2.4 ft), and downgradient (x=4.8 feet) wells.

Figure 2-16. Average bicarbonate alkalinity and pH vs. distance.



Month	June	July	August	October	November	December
UG (Gravel)	19.6	16.8	17.8	16.0	14.3	16.6
Iron	19.4	15.5	5.4	5.0	5.0	5.0
DG (Gravel)	18.5	10.6	5.0	5.0	5.0	5.0

mg/L = milligrams per liter; UG = upgradient; DG = downgradient;
all nondetect values plotted as detection limit (5.0 mg/L)

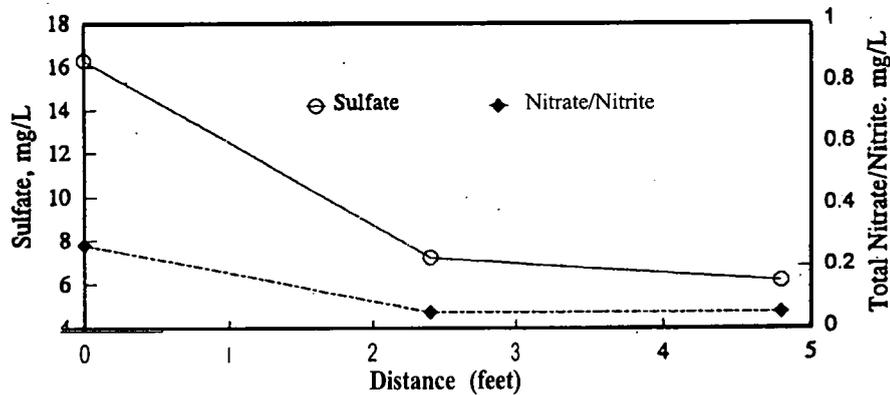
Figure 2-17. Summary of sulfate data over time.



Month	June	July	August	October	November	December
UG (Gravel)	0.477	0.366	0.338	0.256	0.163	0.230
Iron	0.059	0.050	0.050	0.050	0.050	0.050
DG (Gravel)	0.050	0.050	0.050	0.050	0.050	0.050

mg/L = milligrams per liter; UG = upgradient; DG = downgradient;
all nondetect values plotted as detection limit (0.050 mg/L)

Figure 2-18. Summary of total nitrate/nitrite data over time.



Average values based on data from July - December, averaged for: upgradient (X=0 ft); iron (x = 2.4 ft); and downgradient (X=4.8 ft) wells. Detection hit used to represent non-detect values for averaging data.

Figure 2-19. Average sulfate and total nitrate/nitrite values vs. distance.

content varied considerably, but indicated that nitrate was the predominant species. More significantly, the data indicated that total nitrate/nitrite nitrogen was generally not detectable in the samples from the wells screened in the iron or the downgradient pea gravel. According to ETI, nitrate consumption may be due to either **abiotic** or biotic reduction of nitrate to nitrogen gas or ammonium (ETI 1997; PRC 1996). The PLFA analyses did not indicate significant biological activity in the reactive iron; this observation suggests that the decrease in nitrate and sulfate concentrations was primarily due to **abiotic** processes.

Chloride concentrations were determined because they may correlate with dechlorination of VOCs. However, because the background chloride concentrations were relatively high compared to the **influent** VOC concentrations, no significant trends in chloride concentrations were noted during treatment as a result of VOC dechlorination (see Tables C1 - C6).

2.1.5 Objective S-3: Eh, DO, pH, Specific Conductivity, and Temperature

Figures 2-20 and 2-21 summarize the average **pH** values measured in the upgradient pea gravel, iron, downgradient pea gravel, and downgradient aquifer sampling locations during all months of testing. As shown on Figure 2-20, groundwater in the wells screened in the reactive iron typically exhibited the highest **pH** levels during all months of testing. Generally, **pH** increased as groundwater moved from the upgradient pea gravel and through the iron, and then decreased as groundwater moved downgradient. Equations 1-1a through 1-1d, and 1-2a through 1-2g presented in Section 1.3.1 may explain the increase in **pH**. In these reactions, H^+ is consumed so the **pH** rises.

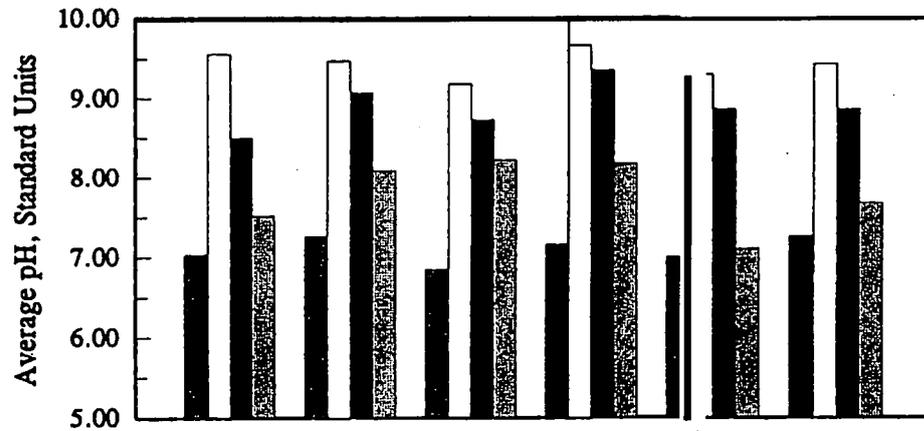
The specific conductivity of groundwater decreased as groundwater moved through the reactive iron, as shown in Figures 2-22 and 2-23. The decrease in the specific conductivity of groundwater is probably caused by the removal of ions from groundwater during treatment. Removal of ions may occur through the formation of metal-hydroxide or metal-carbonate precipitates. The formation of these precipitates may remove metal cations, hydroxyl ions, and carbonate ions from the groundwater.

Generally, the groundwater temperature data did not indicate any significant differences among groundwater

temperatures in the various zones of the cell or in the aquifer. However, the average temperature data indicated a general decrease in site groundwater temperature between October and December. This effect is demonstrated by the average temperature data from the wells screened in the iron zone; these values are summarized in Figure 2-24. The temperature of groundwater in these wells declined about 4° C between October and December. Because the November and December sampling events were performed during cold weather, it is possible that the temperature measurements were affected by ambient air cooling the measuring device. However, due to the shallow depth to groundwater on site, a slight decrease in groundwater temperature in winter months is expected. As discussed in Section 3, according to ETI, past studies involving TCE have shown that temperature can influence the time required for dechlorination to occur (ETI 1996a). However, in this case the slight decrease in temperature did not appear to noticeably affect system performance, and therefore provided no additional data regarding the effects of temperature on the dechlorination process. In general, in-situ systems are less susceptible to potentially adverse ambient temperature effects than aboveground systems.

The dechlorination reactions described by Equations 1-1 and 1-2 indicate a loss of electrons from the oxidizing iron. The groundwater Eh data, summarized in Figures 2-25 and 2-26, indicate that Eh decreased as groundwater moved into the reactive iron, and then increased slightly as groundwater moved downgradient, generally following an opposite trend to the **pH** data. The trends exhibited by the Eh data are consistent with the known electrochemical mechanism of the dechlorination reaction; indicating that electrons derived from the oxidizing iron cause reducing conditions in the groundwater.

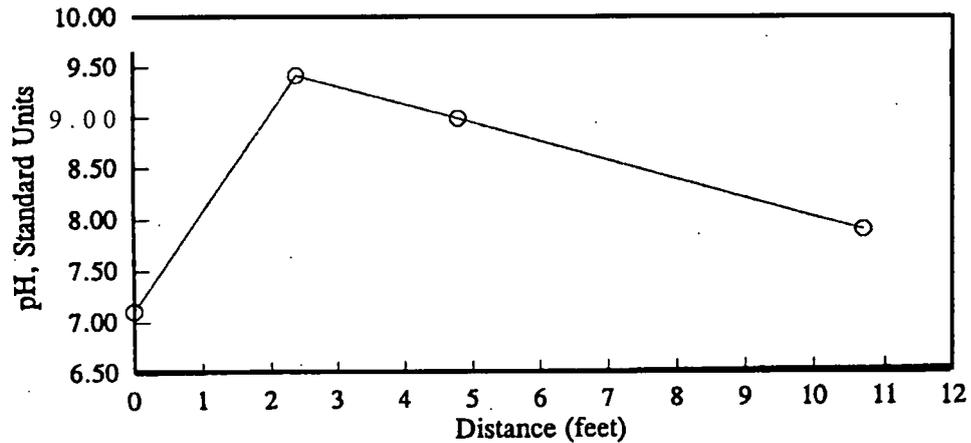
The observed reduction of chlorinated hydrocarbons and the decreases in metals concentrations correlate with the observation that reducing conditions were present. As previously discussed, concentrations of calcium, magnesium, and manganese were observed to decrease coincident with the decrease observed in Eh and the increase in **pH**, and then generally increase as groundwater moved downgradient from the iron wall. However, while trends observed in the Eh data may be indicative of metals precipitating from groundwater moving through the iron, changes in the iron's capacity to dechlorinate the critical contaminants were not observed during the demonstration period.



Month	June	July	August	October	November	December
■ UG (Gravel)	7.03	7.26	6.85	7.16	6.99	7.26
□ Iron	9.56	9.47	9.18	9.67	9.30	9.43
■ DG (Gravel)	8.50	9.07	8.73	9.35	8.86	8.86
■ DG Aquifer	7.51	8.09	8.22	8.17	7.11	7.68

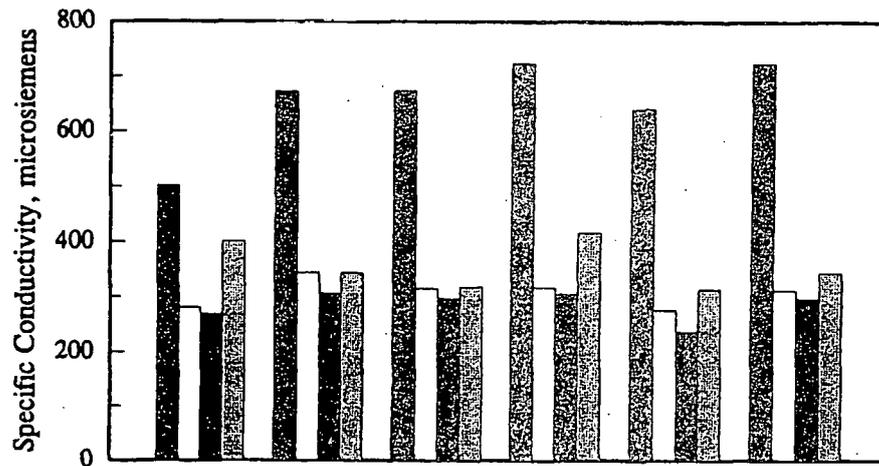
UG = upgradient; DG = downgradient

Figure 2-20. Summary of pH values vs. distance.



Values based on data collected from July - December, averaged for: upgradient (X=0 ft), iron = (X=2.4 ft), downgradient (X=4.8 ft), and downgradient aquifer (X=10.7 ft) wells.

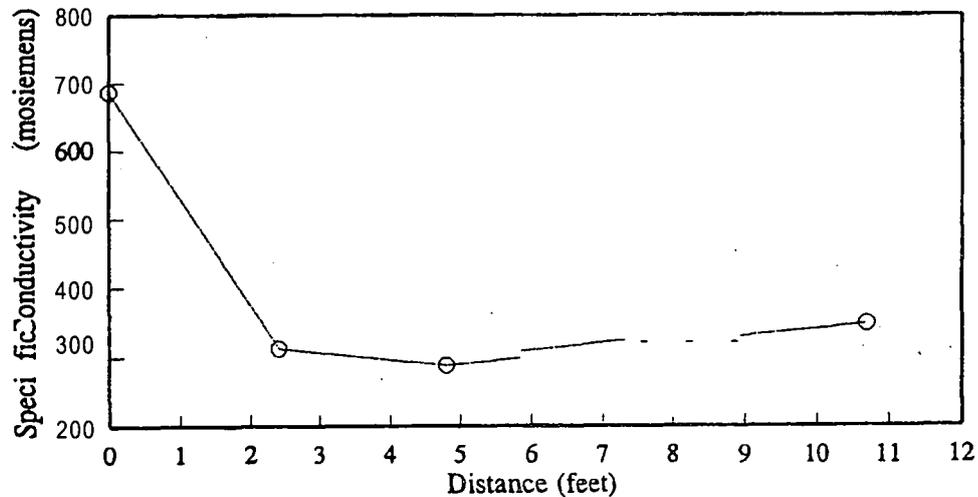
Figure 2-21. Average pH values vs. distance.



Month	June	July	August	October	November	December
■ UG (Gravel)	501	672	673	724	640	724
□ Reactive Iron	280	343	314	316	276	311
■ DG (Gravel)	269	305	297	304	237	296
■ DG Aquifer	400	343	318	415	314	343

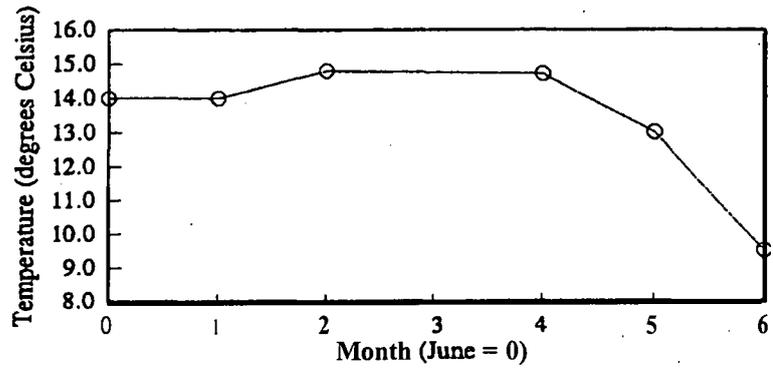
UG = upgradient; DG = downgradient

Figure 2-22. Summary of specific conductivity data over time.



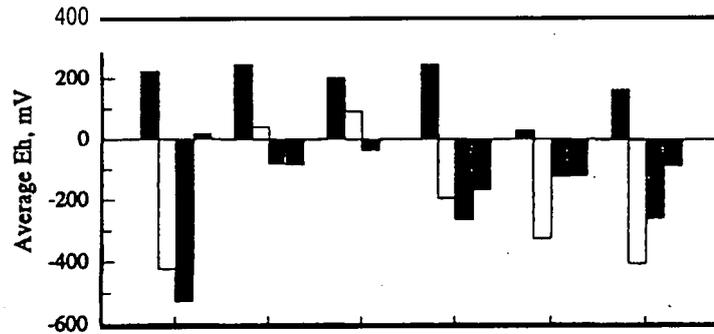
Values based on data from July - December, averaged for: upgradient (X=0 ft); iron (X=2.4 ft); downgradient (X=4.8 ft); and downgradient aquifer (X=10.7 ft) wells.

Figure 2-23. Average specific conductivity values vs. distance.



Values based on data collected from June through December (no data collected in September); values averaged for monitoring wells in reactive iron (MW-Fe1, MW-Fe2, and MW-Fe3).

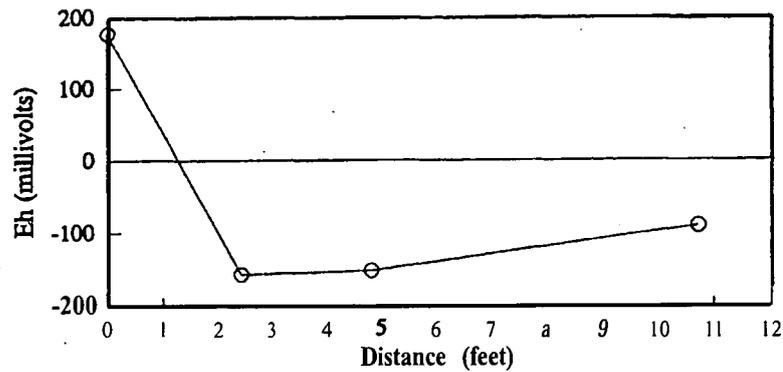
Figure 2-24. Average groundwater temperature in iron wells vs. time.



Month	June	July	August	October	November	December
■ UG (Gravel)	223	246	203	245	30	183
□ Iron	-422	41	92	-194	-325	-405
■ DG (Gravel)	-525	-81	-36	-264	-123	-259
■ DG Aquifer	18	-85	4	-165	-121	-87

mV = millivolts; UG = upgradient; DG = downgradient

Figure 2-25. Summary of Eh data over time.



Values based on data collected from July - December, averaged for: upgradient (X=0 ft); iron (X=2.4 ft); downgradient (X=4.8 ft); and downgradient aquifer (x=10.7 ft) wells.

Figure 2-26. Average Eh values vs. distance.

DO data are not presented in this ITER. The field meter used for DO measurements performed erratically, and lacked the capability of field calibration. For these reasons, the quality of the DO data is unknown, and the DO data are considered unusable.

2.1.6 Objective S-4: Biological Microorganism Growth

According to ETI and others, past studies of the metal-enhanced dechlorination process suggest that the process is **abiotic**, and biological activity does not account for a significant amount of the chlorinated VOC reduction that occurs. During the New York demonstration, the SITE team collected groundwater samples for total PLFA analysis to confirm that the process was predominantly **abiotic**, and to evaluate the potential for excessive microorganism growth that could interfere with hydraulic flow through the iron. PLFA sample fractions were collected in June, October, and December. During each sampling event, the SITE team prepared replicate sample fractions for each well to minimize the potential effects of variability. The PLFA results for the replicate samples from each well were averaged. These average results are presented in Tables C-1 through C-6. Figure 2-27 compares the average total PLFA concentrations for the wells in each row (upgradient pea gravel, reactive iron, downgradient pea gravel, and downgradient aquifer) from each month of testing.

As in the case of the other parameters, the June PLFA data are probably not representative of steady state conditions in the treatment cell. Figure 2-27 shows that for June, the average total PLFA concentration in wells in the treatment cell was on the order of 10^4 to 10^5 picomoles/liter (pm/L). In June there did not appear to be a significant difference between the total PLFA in the upgradient wells, iron wells, and downgradient pea gravel wells. The total PLFA in the downgradient aquifer wells was lower, on the order of 10^3 to 10^4 pm/L. The higher PLFA in the treatment cell and the lack of variance among the PLFA results in the various zones of the cell may be related to residual effects of the cell construction activities, and not indicative of significant long-term microorganism growth in the iron.

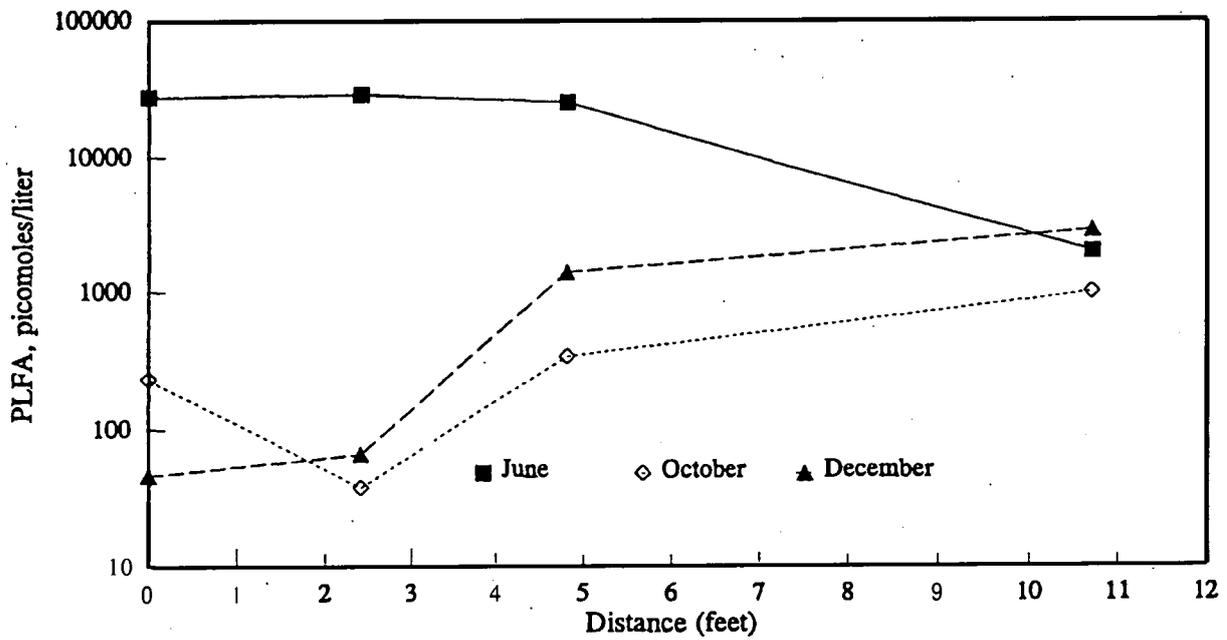
The October and December PLFA data appear to indicate that the total microorganism population in each of the three zones of the treatment cell was significantly lower than in June. PLFA concentrations in the upgradient pea gravel wells were on the order of 10^2 to 10^3 pm/L in

October, and lower yet (10^1 to 10^2 pm/L) in December. This observation may be partially due to the effects of decreasing temperature discussed in Section 2.15. Most significantly, PLFA concentrations in the iron wells in October and December were not significantly higher than in the upgradient pea gravel wells, and were lower than the PLFA concentrations in the downgradient pea gravel and aquifer wells. Total PLFA concentrations in the downgradient aquifer wells in October and December were in the same general range observed in June, before a significant amount of water had passed through the cell and migrated downgradient. These observations suggest that once a sufficient number of pore volumes of water had passed through the system to minimize residual effects of construction activities, the total microorganism population in the pea gravel and the reactive iron was lower than in the natural aquifer materials. For this reason, the results of the PLFA analyses correlate with past research by others indicating that the dechlorination process is **abiotic** (Gillham and O'Hannesin 1994).

As discussed in Section 2.1.7, the groundwater flow velocity estimates were complicated by the low hydraulic gradient. However, there was no measurable decrease in flow velocity over the course of the demonstration. Also, system performance appeared to remain generally consistent throughout the demonstration. For these reasons, biological growth did not appear to be interfering with the flow of groundwater through the reactive iron, further indicating that biological activity in the iron was not significantly greater than in the natural aquifer materials.

2.1.7 Objective S-5: Operating and Design Parameters

Table 2-4 summarizes information collected during the SITE demonstration regarding operating and design parameters. The bulk density analysis of the iron indicated an average (uncompacted) bulk density of approximately 2.25 grams per cubic centimeter, or 140 pounds per cubic foot. About 35 to 40 tons of iron was used to construct the cell; ETI estimates that the bulk density of the iron in the cell was probably greater than the laboratory-measured value due to settling. According to ETI, typical density for iron obtained from the supplier used for the New York Demonstration (Master Builders, Inc.) is about 160 to 180 pounds per cubic foot after settling (ETI 1996a; 1996d; 1997).



Notes: PLFA concentrations are averages for wells in following areas: upgradient pea gravel (X=0 ft); reactive iron (X=2.4 ft); downgradient pea gravel (X=4.8 ft); downgradient aquifer (X=10.7 ft)

Figure 2-27. Total phospholipid fatty acids vs. distance.

Table 2-4. Summary of Operating and Design Parameters

Reactive Iron Medium:	
Initial Weight (ETI)	About 35 to 40 tons
Volume	400 ft ³
Density (uncompacted)	140 lb/ft ³ (2.25 g/cm ³)
Density, after settling, estimated (ETI)	180 lb/ft ³
Hydraulic Conductivity (ETI)	142 ft/day
Porosity, after settling, estimated (ETI)	0.4
Treatment Zone Dimensions:	
Width (thickness) of Iron Wall	3 feet
Length of Iron Wall	12 feet
Height of Iron Wall	11 to 12 feet ¹
Depth of Cell	14 to 15 feet ¹
Width (thickness) of Pea Gravel Zones	About 1.75 feet
Length of Sheet Piling Wings	15 feet each
Aquifer Saturated Thickness (average) ²	10 feet
Hydraulic Gradient Across Iron Wall	Less than 0.001 to 0.002
Width of Capture Zone (ETI) ³	24 feet
Groundwater Flow Velocity through Iron (range)	0.4 to 1 ft/day (ETI)
Volumetric Groundwater Flow Rate (range)	About 15.4 to 57.8 cubic feet (115 to 431 gallons) per day
Cumulative Volume of Water Treated During SITE Demonstration (range) ⁴	About 29,000-73,000 gallons

Notes:

(ETI) - designates value provided by ETI

(range) - range of values provided due to uncertainty in piezometric measurements

¹ Top of reactive iron wall was about 3 feet below ground surface.

² Saturated thickness varied from about 8 to 12 feet, depending on seasonal water table fluctuations.

³ Estimated width of portion of groundwater contaminant plume captured by the funnel and gate system.

⁴ Assumes an average saturated thickness of 10 feet.

Groundwater depth measurements collected during each of the six sampling events were converted to piezometric elevations relative to mean sea level (MSL) to evaluate the horizontal gradient and groundwater flow velocity. The piezometric elevation data are summarized in Table 2-5. Interpretation of the piezometric data was complicated by several factors. As evidenced by the data in Table 2-5, the horizontal gradient measured across the study area was extremely low, generally less than 0.001. This was significantly less than the conservative (maximum) design gradient value (0.002) used by ETI for the system design. In most cases, due to the close spacing of the monitoring wells in the treatment cell and the accuracy limitations of the measuring equipment (0.0 1 foot), differences between water levels in wells in the treatment cell were not accurately measurable. Also, after the in-situ system was installed and the demonstration commenced, S&W detected the presence of a liquid hydrocarbon layer, related to a past release from a UST at the manufacturing facility, on the water table upgradient from the treatment system. This layer prevented piezometric measurements in at least three piezometers (P-2, P-4, and P-7) in the southern part of the demonstration area and may have affected some measurements in other piezometers.¹

Allowing for the limitations of the data, the measurements indicated a generally westward flow direction across the demonstration area, consistent with past data reported by S&W (see Figure 2-28). Based on S&W's reported values for hydraulic conductivity and porosity of the natural aquifer materials, the observed horizontal gradients of 0.0005 to 0.001 indicate groundwater flow velocities of about 0.2 to 0.4 foot per day on site in the aquifer. According to ETI, the funnel and gate configuration typically accelerates flow velocities in the capture zone (PRC1997a). Assuming that the gradient in the treatment cell was at least as high as the natural gradient on site, the minimum estimated flow velocity through the wall was about 0.4 foot per day. Based on the maximum measured gradients between the wells in the cell (December), the maximum estimated flow velocity was about 1 foot per day. These estimates are based on ETI's reported design values for the iron's hydraulic conductivity and porosity (ETI 1994).

Due to the uncertainty regarding the groundwater flow velocity, ETI performed a postdemonstration tracer study and a flow-meter study to evaluate the flow velocity. These studies were not part of the planned SITE demonstration activities, and were not performed under

the direction of EPA. According to ETI, the bromide tracer study was inconclusive; however, the flow meter study indicated a flow velocity of about 1 foot per day in the iron zone (ETI 1996b; 1996d).

In summary, the groundwater flow velocity through the treatment zone appears to have been between 0.4 and 1 foot per day; however, there is uncertainty regarding the flow velocity estimates, and it is possible that the flow velocities were below or above this range. For this reason the exact cumulative volume of groundwater treated during the demonstration is unknown. Assuming the previously-described range of flow velocities and an average saturated thickness of about 10 feet, the volume of groundwater treated was in the range of about 29,000 to 73,000 gallons, and residence time in the 3-foot-thick reactive iron wall appeared to be in the range of about 3 to 7 days. Based on the predominantly nondetectable critical parameter concentrations in the monitoring wells screened in the iron, VOCs appear to have been reduced below regulatory levels within the first 1.5 feet of the reactive iron. For this reason, the high-end (conservative) velocity estimate of 1 foot per day indicates that contaminant dechlorination occurred within 36 hours; the low end estimate (0.4 feet per day) indicates that dechlorination occurred within about 90 hours. In either case, the use of a 3-foot-thick iron wall apparently provided adequate residence time for this particular application during the SITE demonstration period.

2.2 Additional Performance Data

In addition to the SITE demonstration results, several other field applications of the in-situ metal-enhanced dechlorination technology were reviewed to provide additional information about the process. However, the analytical results from these field applications have not been subjected to EPA QA review and therefore are not used to draw conclusions in this report. These applications consisted of (1) the field test conducted at the Canadian Forces Base in Borden, Ontario, Canada (Borden site); (2) a field test and full-scale installation at a California semiconductor facility; and (3) a full-scale installation in Belfast, Northern Ireland. The application of the in-situ metal-enhanced dechlorination process in each of these sites is discussed below. Additional information regarding case studies is presented in Appendix B.

¹ S&W implemented hydrocarbon recovery operations upon discovering the layer. Significant amounts of petroleum-related dissolved-phase contaminants subsequently were not detected and did not affect interpretation of the analytical data.

Table 2-5. Piezometric Data

Location	TOC EL (feet)	TOC EL (feet msl)	<u>6/6/95</u>		<u>7/10/95</u>		<u>8/7/95</u>		<u>10/10/95</u>		<u>11/7/95</u>		<u>12/4/95</u>	
			DTW	GW E L	DTW	GWEL	DTW	GW EL	DTW	GW EL	DTW	GW EL	DTW	GW EL
PI	99.61	1,050.81	7.15	1,043.66	7.96	1,042.85	8.18	1,042.63	8.33	1,042.48	7.62	1,043.19	5.98	1,044.83
P2	100.97	1,052.17	6.51	1,043.66	9.30	1,042.87	9.51	1,042.66	9.86	1,042.31	X	X	X	X
P3	99.60	1,050.80	7.16	1,043.64	7.97	1,042.83	8.17	1,042.63	6.32	1,042.48	7.61	1,043.19	5.99	1,044.81
P4	99.76	1,050.96	7.31	1,043.65	8.11	1,042.85	8.33	1,042.63	X	X	X	X	X	X
P5	99.66	1,050.88	7.23	1,043.65	6.03	1,042.85	0.24	1,042.64	8.39	1,042.49	7.66	1,043.20	6.05	1,044.83
P6	99.41	1,050.61	6.97	1,043.64	7.75	1,042.86	7.98	1,042.63	8.11	1,042.50	7.41	1,043.20	5.76	1,044.85
P7	101.06	1,052.26	9.07	1,043.19	9.95	1,042.31	X	X	X	X	X	X	X	X
P8	100.63	1,051.83	6.14	1,043.69	8.93	1,042.90	9.15	1,042.68	9.31	1,042.52	8.61	1,043.22	6.97	1,044.86
MW-U1	96.76	1,049.98	6.36	1,043.60	7.15	1,042.83	7.37	1,042.61	7.51	1,042.47	6.61	1,043.17	5.17	1,044.81
MW-U2	96.61	1,050.01	6.41	1,043.60	7.18	1,042.83	7.39	1,042.62	7.53	1,042.48	6.62	1,043.19	5.20	1,044.81
MW-U3	96.51	1,049.71	6.11	1,043.60	6.88	1,042.63	7.11	1,042.60	7.24	1,042.47	6.56	1,043.15	4.89	1,044.82
MW-FE1	98.20	1,049.40	6.79	1,042.61	6.57	1,042.83	6.79	1,042.61	6.92	1,042.48	6.22	1,043.18	4.56	1,044.82
MW-FE2	96.05	1,049.25	5.64	1,043.61	6.42	1,042.83	6.64	1,042.61	6.60	1,042.45	6.06	1,043.17	4.43	1,044.82
MW-FE3	96.15	1,049.35	5.74	1,043.61	6.53	1,042.82	6.74	1,042.61	6.67	1,042.48	6.19	1,043.16	4.54	1,044.81
MW-D1	96.81	1,050.01	6.40	1,043.61	7.18	1,042.83	7.40	1,042.61	7.54	1,042.47	6.85	1,043.16	5.22	1,044.79
MW-D2	96.66	1,050.08	6.47	1,043.61	7.25	1,042.83	7.47	1,042.61	7.61	1,042.47	6.91	1,043.17	5.26	1,044.80
MW-D3	98.83	1,050.03	6.42	1,043.61	7.21	1,042.82	7.42	1,042.61	7.57	1,042.46	6.87	1,043.16	5.24	1,044.79
MW-D4	99.20	1,050.40	6.81	1,043.59	7.59	1,042.81	7.61	1,042.59	7.94	1,042.46	7.24	1,043.16	5.62	1,044.78
MW-D5	99.25	1,050.45	6.63	1,043.62	7.62	1,042.83	7.34	1,042.61	7.97	1,042.48	7.28	1,043.17	5.66	1,044.79
MW-D6	96.96	1,050.16	6.55	1,043.61	7.34	1,042.82	7.55	1,042.61	7.69	1,042.47	6.99	1,043.17	5.37	1,044.79

Notes:

All elevation data are based on top-of-casing elevations determined by leveling on 12/4/95; all elevations relative to mean sea level (msl) datum based on data provided by S&W.

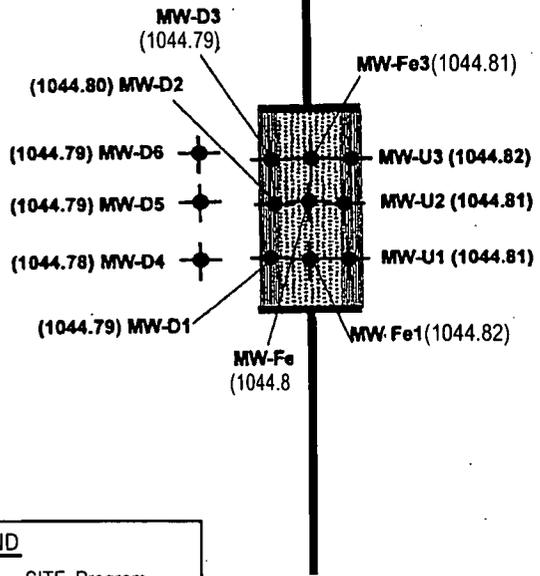
TOC EL=elevation of top of (inner) monitoring well casing.

DTW = depth to groundwater in monitoring well, measured from top of casing.

GW EL = elevation of piezometric surface.

X - Groundwater elevation not measured due to presence of a hydrocarbon layer.

Values in bold type indicate measurements known to be affected by the presence of a hydrocarbon layer.



P3
(1044.81)

P6
(1044.85)

P8
(1044.86)

P5
(1044.83)

P2
NM

P1
(1044.83)

P4
(NM)

P7
(NM)

General
Groundwater
Flow Direction
—————

LEGEND

-  SITE Program Monitoring Well
-  SITE Program Piezometer
- (1044.81)** Piezometric Elevation on
-  Iron Wall (Gate)
-  Pea Gravel

Notes:
All elevations are relative to mean sea level (MSL) datum and are +/- 0.01 foot accuracy.

(NM) - Piezometric elevation not measured due to presence of hydrocarbon layer.

APPROXIMATE SCALE: 1" = 10'

SOURCE: Modified from PRC 1995

45

Figure 2-28. Piezometric elevations-December 1995.

2.2.1 Borden Site

At the Borden site, an in-situ reactive wall was installed in June 1991 to treat groundwater contaminated with PCE and TCE. The source of the plume was located about 13.1 feet below ground surface (bgs) and 3.3 feet below the water table. Maximum contaminant concentrations were about 250,000 and 43,000 $\mu\text{g/L}$ for TCE and PCE, respectively. The permeable wall was constructed about 16 feet downgradient from the source. The aquifer material was a medium to fine sand, and the average groundwater flow velocity was about 0.3 foot per day (Gillham 1995; 1996).

Samples were collected and analyzed over a five-year monitoring period. The results indicate that PCE and TCE concentrations decreased consistently while the concentrations of chloride increased. The average maximum concentrations of PCE and TCE downstream of the wall were about 10 percent of the influent concentration, indicating a substantial reduction within the wall. However, the concentrations of PCE and TCE in the treated water were about three orders of magnitude above site drinking water standards. The results also indicated that cis- and trans- 1,2-DCE were produced as a result of PCE and TCE degradation in the wall. DCE isomers were degraded as they passed through the wall, although effluent concentrations remained above site drinking water standards. No VC was detected in the samples, and no bacterial growth was observed. pH measurements were also taken, the results of which showed little change in pH as a result of treatment (Gillham 1995; 1996). It is suspected that the pH changes normally seen as a result of treatment were not observed because of the buffering capacity of the carbonate sand used during the treatment process. ETI collected core samples of the reactive iron after two years, and again after 3.8 years, to evaluate precipitate formation. According to ETI, examination of samples of the reactive iron using x-ray diffraction and scanning electron microscopy techniques showed no metal precipitates on the iron. (For more information, see O'Hannesin 1993 .)

2.2.2 California Semiconductor Facility

Groundwater from the California semiconductor facility contained TCE at concentrations ranging from 50 to 200 $\mu\text{g/L}$, cDCE ranging from 450 to 1,000 $\mu\text{g/L}$, VC ranging from 100 to 500 $\mu\text{g/L}$, and Freon 113 ranging from 20 to 60 $\mu\text{g/L}$. An above-ground pilot-scale demonstration reactor containing 50 percent iron and 50 percent sand by weight

was installed at the facility and operated for a period of 9 months. Although groundwater at the site is highly mineralized, and precipitate formation was evident, it did not appear to interfere with treatment of the VOCs of concern (Yamane and others 1995; Szerdy and others 1995; Focht, Vogan, and O'Hannesin 1996).

Based on the results obtained from treatment in the reactor, a full-scale in-situ treatment wall was installed in December 1994. The wall consisted of 100 percent granular iron, was 3.9 feet thick, 39.4 feet long, and was situated vertically between depths of about 13 feet and 39.4 feet bgs. A layer of pea gravel, about 1-foot thick, was installed on both the upgradient and downgradient sides of the iron wall (Yamane and others 1995; Szerdy and others 1995; Focht, Vogan, and O'Hannesin 1996).

Since the system was installed, no VOC concentrations exceeding MCLs have been detected in groundwater downgradient from the in-situ system (Yamane and others 1995; Szerdy and others 1995; Focht, Vogan, and O'Hannesin 1996).

2.2.3 Belfast, Northern Ireland Facility

In 1995, a steel, cylindrical, in-situ reactive vessel was installed at a depth of about 40 feet bgs at an industrial facility in Belfast, Ireland. Groundwater at the facility reportedly contains TCE at concentrations as high as 300 mg/L , along with lower concentrations of cDCE and vinyl chloride (ETI 1996c).

The in-situ reactive vessel measures 4 feet in diameter with a vertical thickness of iron measuring 16 feet. Two 100-foot-long slurry walls were installed at the facility to divert groundwater to the reactive vessel. Groundwater flows by gravity through the iron-laden reactive vessel and is discharged from a piped outlet on the downgradient side of vessel. The system was designed to allow about 5 days of residence time. The reactive vessel is equipped with a manhole to access the top of the iron zone in order to scarify the iron surface if a buildup of precipitate should occur. Total cost of the system, including the required design efforts, the slurry walls, the reactive vessel, and the iron was reportedly about \$375,000 (ETI 1996c).

Since installing the reactive vessel, TCE concentrations in effluent groundwater have been reduced to less than 100 $\mu\text{g/L}$, and cDCE concentrations have been reduced to less than 10 $\mu\text{g/L}$ (ETI 1996c).

Section 3 Technology Applications Analysis

This section discusses the following topics regarding the applicability of the metal-enhanced dechlorination technology: factors affecting technology performance, site characteristics and support requirements, material handling requirements, technology limitations, potential regulatory requirements, and state and community acceptance. This section is based on the results of the New York site demonstration and additional information provided by ETI and other sources.

3.1 Factors Affecting Performance

Factors potentially affecting the performance of the metal-enhanced dechlorination process include feed waste characteristics, site hydrogeology and maintenance requirements.

3.7.1 Feed Waste Characteristics

Feed waste characteristics that may affect the performance of the metal-enhanced dechlorination technology include the types and concentrations of organic and inorganic substances present in the groundwater to be treated, and geochemical parameters such as pH and possibly temperature.

Organic Compounds

According to ETI, the metal-enhanced dechlorination technology has successfully degraded many halogenated VOCs. These compounds are PCE; TCE; cDCE; tDCE, 1,1-dichloroethene; VC; TCA; trichloromethane; 1,2-dibromoethane; 1,2,3-trichloropropane; 1,2-dichloropropane; 1,1-dichloroethane and Freon 113. Although the degradation of compounds such as chloromethane, dichloromethane, 1,2-dichloroethane, and 1,4-dichlorobenzene is thermodynamically favorable, these compounds have either not been observed to degrade

in the presence of iron or have not been studied in detail (Gillham 1996; Focht, Vogan and O'Hannesin 1996).

The performance of the metal-enhanced dechlorination technology is typically evaluated based on the half-lives of the compounds that it dechlorinates. The half-life is defined as the time required to degrade a compound to one-half of its original concentration in the medium being treated. The half-lives of the different VOCs vary depending on concentration and other site-specific factors. Half-lives using treatment by the metal-enhanced dechlorination process generally appear to be less than those reported for biological and other natural subsurface abiological processes (Gillham 1996).

Although the reported half-lives for a particular compound will vary, half-lives generally tend to increase with decreasing degrees of chlorination. This is particularly evident when considering a single group of compounds, such as chlorinated ethenes. PCE and TCE degrade at reasonably similar rates; the rate is lower for DCE, and lower yet for VC. This trend is consistent with reductive dechlorination, since the most highly chlorinated compounds are the most oxidized and would be expected to be the least stable under reducing conditions (Gillham and O'Hannesin 1994; Gillham 1996).

Although many chlorinated VOCs can be degraded in the presence of iron, further studies are required for many of the VOCs to evaluate the occurrence of toxic and persistent degradation products. In addition, the degradation products generally degrade at much lower rates than the parent compound (ETI 1994; Focht, Vogan and O'Hannesin 1996). Therefore, even though they occur at much lower concentrations, degradation products may be more critical than parent compounds with regard to determining the required residence time in the design of metal-enhanced dechlorination technology systems.

Inorganic Compounds

Recent research has indicated that hexavalent chromium may be reduced by reactive iron. At a recent installation involving a chlorinated VOC plume that also contained hexavalent chromium, ETI observed that total chromium was nondetectable downgradient from the system. Past studies by others have also indicated the iron's potential to reduce hexavalent chromium (Puls, Powell and Paul 1995). However, this potential application of the technology has not been tested extensively.

The effect of inorganic compounds on the VOC degradation process may represent the greatest uncertainty with respect to the long-term, low-maintenance operation of the in-situ metal-enhanced dechlorination technology. At the elevated pH levels induced by the dechlorination reaction, the Fe^{2+} produced by the oxidation of the zero valent iron may precipitate as $Fe(OH)_2$, depending on the DO concentration and provided that Eh is sufficiently low. Iron may also precipitate as $FeCO_3$, depending on the carbonate concentration of the influent groundwater. Carbonate precipitates of calcium, magnesium, barium, and other metals may also form, particularly in the portion of the iron along the upgradient face of the wall.

Excessive buildup of metal precipitates may limit the flow of groundwater through the treatment system. It is also possible that precipitates may block the iron surfaces available for reaction causing a reduction in the iron's reactive capacity over time, or decrease the dechlorination reaction rate. Based on the results of the New York demonstration, ETI estimates that formation and deposition of metal precipitates during treatment could cause about 4 to 7.5 percent of the original porosity in the iron to be lost annually (ETI 1996a). However, the amount of porosity loss is site specific; ETI reports projected porosity losses ranging from 2 to 15 percent per year in studies involving water from other sites. The extrapolation of these estimates to field-scale systems depend on the kinetics of precipitation under field conditions (Fochf Vogan, and O'Hannesin 1996).

Site- and waste-specific treatability studies are required to identify potential precipitates and the rates at which they may form; possible effects on the reductive dechlorination rate and system hydraulics; and factors that may control precipitate formation. O&M procedures may need to compensate for the formation of precipitates during treatment of highly mineralized water. Before proceeding

with a full-scale remediation, it may be necessary to develop operating methods to prevent precipitate formation or maintenance techniques to periodically remove precipitates once they form.

3.1.2 Hydrogeologic Characteristics

Site hydrogeology significantly affects the performance of the in-situ metal-enhanced dechlorination technology by controlling 1) the implementability of the technology; 2) selection of the type of system (continuous wall or funnel and gate); and 3) design parameters for the reactive iron wall.

The technology's implementability is affected by the depth to and saturated thickness of the aquifer. Many chlorinated VOCs tend to sink when released in free phase to an aquifer, often causing dissolved-phase contaminants to be more concentrated in deeper portions of the aquifer. For this reason, the technology is most effective when it can be installed to completely intercept flow over the entire saturated thickness of the aquifer. If possible, the base of the iron wall should be keyed into an underlying aquiclude to prevent untreated water from flowing beneath the wall. As in any technology that requires trenching activities, the technology is more easily implemented at shallower depths (less than 50 feet). Also, if possible, the top of the wall should be high enough to prevent seasonal fluctuations in the water table from causing untreated water to flow over the wall. However, extension of the iron above the seasonal high water table may not be practical for extremely shallow aquifers, as it is preferable to keep the top of the iron within the saturated zone to prevent exposure to air and excessive oxidation. ETI currently designs systems to cover as much of the vertical extent of the saturated zone as possible while still allowing about 3 feet above the iron for a dense soil cover to prevent excessive "rusting."

For these reasons, shallow unconsolidated aquifers overlying dense clay or tight bedrock at depths less than 50 feet are more ideally suited for this technology than bedrock aquifers or deep aquifers in general. However, methods to facilitate deeper applications of this technology are currently being studied and at least one deep installation (greater than 100 feet deep) was planned for design at the time of this report (Appleton 1996).

3.1.3 Operating Parameters

Based on information provided by the developer, several operating parameters that may affect system performance were identified. These parameters include (1) iron surface area-to-groundwater volume ratio, (2) **pH**, (3) residence time, and (4) temperature of the reactor and **influent** water.

Ratio of Iron Surface Area to Groundwater (Solution) Volume

A precise quantitative correlation between the iron surface area-to-water volume ratio on the dechlorination reaction rate has not been established. Experimental results indicate that the rate of dechlorination increases as the ratio of iron surface area-to-groundwater volume increases. For this reason increasing the iron surface area in contact with the water at any given time should increase the dechlorination reaction rate, provided all other factors remain constant (Gillham and O'Hannesin 1994; Gillham 1996). Based on this rationale, it appears that reductions in the amount of iron surface area, possibly caused by precipitates forming a coating on the reactive iron granules, could increase contaminant half-lives.

pH

As previously discussed, the reactions which accompany the dechlorination process cause **pH** to increase as water dissociates to form H_2 gas and hydrogen ions substitute for chlorine atoms. This observation suggests that unusually high or low **influent pH** in the **influent** groundwater may affect the dechlorination reaction. However, the effects of varying **pH**, and other geochemical parameters (such as DO and Eh) in the **influent** groundwater were not evaluated in detail during the SITE demonstration, as **influent** groundwater **pH** was relatively constant throughout the demonstration period.

Residence Time

Residence time is the time required for a "particle" of groundwater to flow through a reactive iron treatment wall in an in-situ installation, or through the iron layer in an aboveground reactor. For any particular application, the residence time of groundwater in the treatment medium must be sufficient to reduce **influent** concentrations of VOCs and potential dechlorination by-products to cleanup standards.

To treat groundwater containing several chlorinated VOCs having the potential to form multiple dechlorination by-products, the total required residence time is calculated as the sum of the estimated residence times required for dechlorination of the compounds that have the longest half-lives. For example, the design of the m-situ wall at the New York site was based on maximum projected half-lives of about 0.2 hour for TCE, 3.7 hours for **cDCE**, and 1.2 hours for VC. ETI estimated a required residence time of about 55 hours for the pilot-scale system, assuming that **cDCE** would require the longest residence time of any of the compounds (37 hours), due to the greater amount of **cDCE** relative to the amount of iron to be used in the system. ETI conservatively assumed that no VC dechlorination would occur until **cDCE** dechlorination was complete. The bench-scale studies indicated that the other compounds suspected to be present (PCE, **tDCE**, and TCA) would dechlorinate simultaneously with the other compounds, not requiring additional residence time (ETI 1994).

In an in-situ system, residence time is controlled by the groundwater flow velocity and the thickness of the reactive iron wall. The appropriate thickness is determined by dividing the required residence time by the groundwater flow velocity (the natural flow velocity for continuous walls, or an accelerated velocity projected for a proposed funnel and gate system). The wall must be thick enough to allow adequate time for chlorinated VOCs to be reduced from **influent** concentrations to the applicable water quality criteria, and must also allow **sufficient** time for dechlorination of any by-products. The thickness of the wall should also incorporate a contingency factor to allow for seasonal fluctuations in flow velocity. For some applications, extra width may also be appropriate to allow for decreases in the performance of the upgradient portion of the iron due to precipitate formation over time.

In an aboveground reactor, water typically flows vertically through a reactive iron bed by gravity. The residence time (volume of pore space in the reactive iron layer divided by volumetric flow rate) is controlled by the hydraulic head (which can be controlled by the **influent** pumping rate); pore volume, hydraulic conductivity, and thickness of the reactive iron layer; and the configuration of the effluent piping. The results of a previous SITE demonstration of an aboveground application of this technology suggested that the same general design criteria apply as for in-situ systems; that is, the iron layer must be sufficiently thick to

allow adequate residence time for dechlorination of parent compounds and potential dechlorination by-products.

Temperature

According to ETI, laboratory testing has indicated that temperature affects the reaction rate for the dechlorination of TCE, and presumably would affect reaction rates for other compounds as well (ETI 1996a). Data gathered at a previous SITE Program demonstration of an aboveground system indicated that a gradual decline in reactor temperature and the temperature of groundwater in the reactor coincided with an apparent increase in the length of time chlorinated VOCs persisted in the reactive iron bed. However, data were **insufficient** to differentiate possible temperature effects from other factors that may have affected system performance (EPA 1997).

During the New York demonstration, data indicated a gradual lowering of groundwater temperature in the last 2 months of the demonstration. Unlike the demonstration of the aboveground reactor, there was no measurable increase in the length of time required for TCE dechlorination coincident with the temperature decline. However, because TCE was generally below detectable levels in the samples from the wells screened in the iron, the length of time actually required for TCE dechlorination to occur is unknown. For this reason, it is possible that slight decreases in the TCE dechlorination reaction rate occurred during the New York demonstration, but were not detectable.

In general, in-situ remediation systems tend to be less susceptible to temperature fluctuations than aboveground systems. However, typical groundwater temperatures are usually less than the ambient temperatures at which laboratory treatability studies are performed. For extremely shallow aquifers, groundwater temperature may fluctuate significantly, particularly in climates that experience extreme ranges in seasonal temperature and precipitation. If temperature does affect the reaction rate, colder temperatures could increase the required residence time. For these reasons, seasonal groundwater temperature should be considered in the system design; design allowances (extra width) may be necessary if preconstruction studies indicate a potential for temperature decrease to affect the dechlorination reaction rates.

3.1.4 Maintenance Requirements

The maintenance requirements for the in-situ metal-enhanced dechlorination system summarized in this section are based on observations of the pilot-scale system used during the SITE demonstration; assumptions based on the analytical data; results of previous applications of the technology; and discussions with ETI personnel.

Metals precipitating from groundwater may accumulate and physically block the pore spaces on the **influent** side of the reactive iron medium, reducing flow. Also, metal precipitates may coat the reactive iron surface, reducing the surface area available for contact with contaminated groundwater. Precipitate formation will vary depending on a number of site-specific factors. According to ETI, precipitates tend to concentrate in the first few inches on the **influent** side of the reactive iron. However, because relatively few in-situ systems have been operating for more than 2 years (at the time of this report), knowledge of long-term trends in and effects of precipitate formation is primarily based on extrapolations from bench scale studies or short-term observations from recent field applications.

Maintenance procedures to counteract the effects of precipitate formation for in-situ systems have not been extensively tested in the field; however, ETI is currently studying methods of in-situ chemical or physical treatment of the iron to remove precipitates. Possible chemical methods considered include dissolving precipitates by introducing mild acids upgradient from the wall; however, this technique currently does not appear feasible for most situations as the acid would also probably react with the iron and cause excessive corrosion. Physical techniques include scarifying or agitating the upgradient side of the iron wall. ETI has suggested the use of soil augers or mixing equipment at the interface between the natural aquifer materials (or pea gravel, if present) and the **influent** side of the iron to accomplish this task. However, this technique has not yet been attempted at existing in-situ installations and is untested under actual field conditions at the time of this report. ETI estimates that some form of maintenance to remove precipitates may typically be required every 5 to 10 years (Focht, Vogan, and O'Hannesin 1996).

If maintenance techniques are not successful, periodic replacement of the iron may be necessary for long-term (greater than 10 year) remedial programs. For some

applications, it also may be possible to allow a sufficient thickness contingency in the reactive iron wall to compensate for reactivity losses caused by reductions in the available reactive iron surface area. However, this would not necessarily alleviate problems associated with significant reduction of the iron's hydraulic conductivity.

Biological growth in the reactive iron did not appear to be a significant problem during the New York in-situ demonstration (PRC 1997). Long term performance data for in-situ systems under a wide range of conditions are limited; therefore, potential operating problems caused by long-term biological growth have not been studied extensively.

3.2 Site Characteristics and Support Requirements

Site-specific factors can impact the application of the in-situ metal-enhanced dechlorination process, and these factors should be considered before selecting the technology for remediation of a specific site. Site-specific factors addressed in this section are site access, area, and preparation requirements; climate; utility and supply requirements; support systems; and personnel requirements.

According to ETI, both in-situ treatment wall installations and aboveground treatment reactors are available (see Section 5, Technology Status, and Appendix A, Vendor's Claims for the Technology). The support requirements of these systems vary. This section presents support requirements based on the information collected for the in-situ treatment system used at the New York demonstration site.

3.2.1 Site Access, Area, and Preparation Requirements

In addition to the hydrogeologic conditions that determine the technology's applicability and design, other site characteristics affect implementation of this technology. The actual amount of space required for an in-situ system depends on the required thickness and length of the reactive iron wall, and whether a continuous wall or funnel and gate system are used. For the New York demonstration, the gate section comprised an area about 12 feet by 6.5 feet (including the 3-foot-thick iron wall and the adjacent pea gravel sections) in plan. In addition, the end sections comprising the funnel extended the length of the system by 15 feet on each end. According to ETI, the

system captured a 24-foot-wide portion of the 300-foot-wide plume. A full-scale funnel and gate system would typically consist of several interspersed funnels and gates or a continuous iron wall across the entire width of the plume. A system employing a continuous wall would probably not be as thick as it would not employ flanking sections of pea gravel; for example, ETI estimates that a 1-foot-thick wall may be adequate to treat groundwater under the general conditions observed at the New York site. (According to ETI, the effects of anisotropic flow are less critical for continuous walls than for funnel and gate systems because the continuous walls are not expected to accelerate groundwater flow velocity.) In either case, the length of the system will depend on the size of the contaminant plume. Sufficient space must also be available for monitoring wells upgradient and downgradient from the system.

The site must be accessible to and have sufficient operating and storage space for heavy construction equipment. Excavating equipment is necessary to prepare a subsurface trench. For funnel and gate systems, a crane equipped with a pile driver is necessary to install sheet piling and to subsequently remove the sheet piling from the upgradient and downgradient sides of the gate. Access for tractor trailers (for delivery of iron, construction supplies, and equipment) is preferable. A front-end loader may be needed to place the iron in the trench. Access for a drill rig to install the wells for system performance monitoring will be required, unless the wells are constructed as integral parts of a treatment "cell." Underground utilities crossing the path of the proposed system may need to be relocated if present, and overhead space should be clear of utility lines, to allow cranes and drill rigs to operate. The wall may need to be constructed around existing surface structures that are on site.

Soils excavated at sites contaminated with chlorinated VOCs may require management as a potentially hazardous waste. For this reason, roll-off boxes to hold the soil, and sufficient space near, but outside of the construction area for staging the boxes should be available. In addition, a portable tank or tanker truck should also be available for funnel and gate installations to temporarily hold water removed from the trench.

3.2.2 Climate Requirements

Because the in-situ metal-enhanced dechlorination process is completely below grade and usually requires no aboveground piping or utilities, the system does not

appear to be significantly affected by ambient weather conditions. For this reason, the system can be installed and operated in virtually any climatologic zone. However, variations in groundwater temperature may need to be considered in the system design (see Section 3.1.3.)

3.2.3 Utility and Supply Requirements

Existing on site sources of power and water may facilitate, but are not required, for construction activities. After the initial construction phase, the in-situ funnel and gate system at the New York site required no electrical power or other utility support.

Supply requirements specific to the technology may include fresh iron medium to replace iron that has lost an unacceptable amount of its reactive capacity. The frequency at which iron may need to be replaced is highly site-specific (see Section 3.1.4). Other supplies indirectly related to the technology include typical groundwater sampling supplies that will be used for system monitoring.

3.2.4 Required Support Systems

No pretreatment of groundwater is necessary for in-situ systems. As discussed in Section 1.3, potential users of this technology must consider the possibility that the dechlorination of some multi-chlorinated compounds such as PCE and TCE may generate by-products such as cDCE and VC. Properly designed systems allow sufficient residence time to dechlorinate these compounds; however, in-situ system designs may need to allow for additional posttreatment "polishing" of system effluent in the event that byproducts such as cDCE and VC persist. In such cases, contingent systems such as air **sparging/soil** vapor extraction (SVE) combined with carbon adsorption of the effluent vapors may be appropriate.

S&W initially installed two PVC air sparging wells in the downgradient pea gravel zone, as a contingency so that an air **sparging/SVE** system could be rapidly constructed in the event that persistent dechlorination by-products such as cDCE or VC were detected downgradient from the wall. However, the in-situ system appeared to consistently reduce concentrations of all critical parameters and potential by-products during the demonstration period. For this reason, posttreatment was not implemented during the demonstration.

3.2.5 Personnel Requirements

Personnel requirements for the system are minimal. Site personnel must collect periodic samples to evaluate system performance. Also, personnel should periodically inspect the system for general operating condition. Personnel should check water levels in the monitoring wells and piezometers to ensure continuing flow through the wall, and inspect the condition of the wells and piezometers. Personnel should also inspect the condition of the ground surface above the system and identify any indications of potential problems, such as severe subsidence or erosion. If possible, representative core samples should be periodically obtained to evaluate precipitate formation. If support systems (such as air **sparging/SVE**) are used, additional on-site personnel may be required.

Personnel requirements for long-term maintenance will depend on the type of maintenance activities. If soil mixing, drilling, iron replacement, or other activities requiring specialized heavy equipment will be performed, trained equipment operators will be required.

Personnel working with the system at a hazardous waste site should have completed the training requirements under the Occupational Safety and Health Act (OSHA) outlined in 29 CFR 1910.120, which covers hazardous waste operations and emergency response. Personnel also should participate in a medical monitoring program as specified under OSHA.

3.3 Material Handling Requirements

Material handling requirements for the in-situ **metal-enhanced** dechlorination technology include those for the soil and water removed from the excavation, the reactive iron medium, and the pea gravel or well-sand used in the construction of the system. Groundwater removed by trench dewatering will probably contain chlorinated VOCs. Also, soils excavated from below the water table in the vicinity of a chlorinated VOC plume may have become contaminated by contact with contaminated groundwater. For this reason, soil and water generated by construction activities may require handling, storage, and management as hazardous wastes. Precautions may include availability of lined, covered, roll-off boxes, drums, or other receptacles for the soil; solvent-resistant storage tanks for the water; and appropriate personal protective equipment (PPE) for handling materials containing chlorinated

VOCs. Soils from the vadose zone should be stockpiled on site separately from soils excavated from below the water table, to minimize the amount of material requiring management as potentially hazardous waste.

Precautions required for the handling of the iron and pea gravel include those normally employed for nuisance dusts, including the use of respiratory protection.

3.4 Technology Limitations

The in-situ metal-enhanced dechlorination technology is limited by the ability of the reactive iron to treat wastestreams containing only certain chlorinated VOCs, which limits the number of sites for which the technology may be ideally suited. Sites involving multiple types of groundwater contaminants may not be ideally suited for this technology.

Although recent studies by ETI and others have indicated that other contaminants (for example, hexavalent chromium, uranium and some other metals; some brominated compounds; and some pesticides) may be reduced by the technology, the reactive iron either cannot reduce, or has not yet been extensively shown to reduce, nonchlorinated organic compounds, some chlorinated VOCs (such as chloromethane, dichloromethane, 1,2-dichloroethane, and 1,4-dichlorobenzene); some metals, and other chlorinated organic compounds such as chlorinated phenols and most pesticides (ETI 1997; Focht, Vogan, and O'Hannesin 1996). Aboveground systems or other, conventional ex-situ technologies can often be modified by adding modular, in-line pretreatment or posttreatment components to treat multiple types of contaminants. However, auxiliary treatment systems that are technically adaptable to the in-situ metal-enhanced dechlorination process appear to be limited to conventional in-situ technologies associated with VOC removal, such as air sparging and SVE.

The second limitation concerns the reactive iron medium's usable life before its reactivity or hydraulic conductivity are significantly reduced by the formation of metal precipitates. Information regarding the useful life of the iron is limited because no long-term (exceeding 5 years) performance data are currently available. As discussed in Section 1.3, the driving force of the dechlorination reaction is the corrosion of iron, or the conversion of Fe^0 to Fe^{2+} . According to ETI, the measured corrosion rate of iron indicates that iron will persist for

several years to decades, depending on the concentration of VOCs in the groundwater and the flow rate through the iron (Focht, Vogan, and O'Hannesin 1996). However, deposition of metal precipitates on the reactive iron medium may adversely affect system hydraulics or block the reactive surface area of the iron particles. Although ETI is researching maintenance techniques to counteract these effects, the proposed techniques are unproven under representative full-scale field conditions at the time of this report.

During the New York demonstration, no decline in the system's ability to dechlorinate the target compounds was noted, although the inorganic data and geochemical parameters suggested that metal precipitates were forming in the iron. However, in a previous SITE Program demonstration of an aboveground application of the metal-enhanced dechlorination technology, "parent" chlorinated VOCs were observed to persist longer as the demonstration progressed. This effect was accompanied by the appearance of low concentrations of dechlorination by-products (cDCE and VC) in the effluent. Although other factors may have contributed to the decline in performance, geochemical data indicated that metal precipitates were forming, and subsequent studies performed by ETI confirmed that a hard precipitate layer had formed in the upper (influent) portion of the reactive iron bed (EPA 1997).

A third limitation of the technology is that passive systems do not necessarily remove the contaminant source. Although the system may be able to treat all of the contaminated groundwater migrating from a site, contaminant sources upgradient from the system (such as subsurface soils) may continue to release chlorinated VOCs to groundwater until an aggressive remediation scheme, such as removal, is enacted. For this reason, to achieve overall permanent remediation of a site, the technology may be most successful if implemented in conjunction with additional source reduction activities.

The fourth limitation pertains to the practicality of implementing the technology at some sites. As for most fully penetrating, in-situ containment/treatment systems, the need for intrusive construction activities requires significant amounts of open surface space, possibly precluding use of this technology at some sites. Also, the limitations of trench construction technologies tend to make fully penetrating systems best-suited for installations shallower than 50 feet, and often less for some soil types.

ETI has successfully used continuous excavation/backfill technology to install reactive iron walls, eliminating many of the time requirements, construction costs, and safety concerns associated with conventional trenching activities, and future applications may test the use of deep borings and hydraulic fracturing to install systems at greater depths (Appleton 1996). However, ETI's deepest existing in-situ system is about 40 feet deep. Also, the technology may be less effective in aquifers lacking a suitable underlying aquitard (for keying the base of the iron wall).

3.5 Potential Regulatory Requirements

This section discusses regulatory requirements pertinent to using the in-situ metal-enhanced dechlorination process at Superfund, Resource Conservation and Recovery (RCRA) corrective action, and other cleanup sites. The regulations pertaining to applications of this technology depend on site-specific conditions; therefore, this section presents a general overview of the types of federal regulations that may apply under various conditions. State and local requirements should also be considered. Because these requirements will vary, they are not presented in detail in this section. Table 3- 1 summarizes the environmental laws and associated regulations discussed in this section.

During the SITE demonstration of the in-situ metal-enhanced dechlorination process no groundwater was pumped from the affected aquifer to above the ground surface. Therefore, many state and federal regulations applicable to the pumping, treatment, and disposal or discharge of contaminated groundwater were not relevant to this particular application, nor would they be relevant when this technology is used in similar fashion at other sites. If required, auxiliary posttreatment processes will likely involve additional regulatory requirements that would need to be addressed. This section focuses on regulations applicable to the in-situ metal-enhanced dechlorination technology, and briefly discusses regulations that may apply if posttreatment is required.

3.5. 1 Comprehensive Environmental Response, Compensation, and Liability Act

The Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), as amended

by SARA, authorizes the federal government to respond to releases of hazardous substances, pollutants, or contaminants that may present an imminent and substantial danger to public health or welfare. CERCLA pertains to the metal-enhanced dechlorination system by governing the selection and application of remedial technologies at Super-fund sites. Remedial alternatives that significantly reduce the volume, toxicity, or mobility of hazardous substances and provide long-term protection are preferred. Selected remedies must also be cost-effective, protective of human health and the environment, and must comply with environmental regulations to protect human health and the environment during and after remediation.

CERCLA requires identification and consideration of environmental requirements that are ARARs for site remediation before implementation of a remedial technology at a Superfund site. Subject to specific conditions, EPA allows ARARs to be waived in accordance with Section 121 of CERCLA. The conditions under which an ARAR may be waived are (1) an activity that does not achieve compliance with an ARAR, but is part of a total remedial action that will achieve compliance (such as a removal action), (2) an equivalent standard of performance can be achieved without complying with an ARAR, (3) compliance with an ARAR will result in a greater risk to health and the environment than will noncompliance, (4) compliance with an ARAR is technically impracticable, (5) a state ARAR that has not been applied consistently, and (6) for fund-lead remedial actions, compliance with the ARAR will result in expenditures that are not justifiable in terms of protecting public health or welfare, given the needs for funds at other sites. The justification for a waiver must be clearly demonstrated (EPA 1988a). Off-site remediations are not eligible for ARAR waivers, and all applicable substantive and administrative requirements must be met. Depending on a particular application, posttreatment (secondary treatment) such as air **sparging/SVE** may be used in conjunction with the in-situ metal-enhanced dechlorination technology, requiring air emissions and effluent discharge either on or off site. CERCLA requires on-site discharges to meet all substantive state and federal ARARs, such as effluent standards. Off-site discharges must comply not only with substantive ARARs, but also state and federal administrative ARARs, such as permitting, designed to facilitate implementation of the substantive requirements.

Table 3-1. Summary of Environmental Regulations

Act/Authority	Applicability	Application to the In-Situ Metal-Enhanced Dechlorination Technology	Citation
CERCLA	Cleanups at Superfund sites	This program authorizes and regulates the cleanup of releases of hazardous substances. It applies to all CERCLA site cleanups and requires that other environmental laws be considered as appropriate to protect human health and the environment.	40 CFR part 300
RCRA	Cleanups at Superfund and RCRA sites	RCRA regulates the transportation, treatment, storage, and disposal of hazardous wastes. RCRA also regulates corrective actions at treatment, storage, and disposal facilities.	40 CFR parts 260 to 270
CWA	Discharges to surface water bodies	NPDES requirements of CWA apply to both Superfund and RCRA sites where treated water is discharged to surface water bodies. Pretreatment standards apply to discharges to POTWs . These regulations do not typically apply to in-situ technologies.	40 CFR parts 122 to 125, part 403
SDWA	Water discharges, water re injection , and sole-source aquifer and wellhead protection	Maximum contaminant levels and contaminant level goals should be considered when setting water cleanup levels at RCRA corrective action and Superfund sites. Sole sources and protected wellhead water sources would be subject to their respective control programs.	40 CFR parts 141 to 149
CAA	Air emissions from stationary and mobile sources	If VOC emissions occur or hazardous air pollutants are of concern, these standards may be applicable to ensure that use of this technology does not degrade air quality. State air program requirements also should be considered.	40 CFR parts 50, 60, 61, and 70
AEA and RCRA	Mixed wastes	AEA and RCRA requirements apply to the treatment, storage, and disposal of mixed waste containing both hazardous and radioactive components. OSWER and DOE directives provide guidance for addressing mixed waste.	AEA (10 CFR part 60) and RCRA (see above)
OSHA	All remedial actions	OSHA regulates on-site construction activities and the health and safety of workers at hazardous waste sites. Installation and operation of the metal -enhanced dechlorination process at Superfund or RCRA cleanup sites must meet OSHA requirements.	29 CFR parts 1900 to 1926
NRC	All remedial actions	These regulations include radiation protection standards for NRC-licensed activities.	IO CFR part 20

3.5.2 Resource Conservation and Recovery Act

RCRA, as amended by the Hazardous and Solid Waste Amendments of 1984, regulates management and disposal of municipal and industrial solid wastes. EPA and the states implement and enforce RCRA and state regulations. Some of the RCRA Subtitle C (hazardous waste) requirements under 40 CFR parts 264 and 265 may apply at CERCLA sites because remedial actions generally involve treatment, storage, or disposal of hazardous waste. However, RCRA requirements may be waived for CERCLA remediation sites, provided equivalent or more stringent ARARs are followed.

Use of the in-situ metal-enhanced dechlorination technology may constitute "treatment" as defined under RCRA regulations in Title 40 of the Code of Federal Regulations (40 CFR) 260.10. Because treatment of a hazardous waste usually requires a permit under RCRA, permitting requirements may apply if the technology is used to treat a listed or characteristic hazardous waste. Regulations in 40 CFR part 264, subpart X, which regulate hazardous waste storage, treatment, and disposal in miscellaneous units, may be relevant to the metal-enhanced dechlorination process. Subpart X requires that in order to obtain a permit for treatment in miscellaneous units, an environmental assessment must be conducted to demonstrate that the unit is designed, operated, and closed in a manner that protects human health and the environment. Requirements in 40 CFR part 265, subpart Q (Chemical, Physical, and Biological Treatment), could also apply. Subpart Q includes requirements for waste analysis and trial tests. RCRA also contains special standards for ignitable or reactive wastes, incompatible wastes, and special categories of waste (40 CFR parts 264 and 265, subpart B). These standards may apply to the in-situ metal-enhanced dechlorination technology, depending on the waste to be treated.

In the event the in-situ metal-enhanced dechlorination technology is used to treat contaminated liquids at hazardous waste treatment, storage, and disposal facilities as part of RCRA corrective actions, regulations in 40 CFR part 264, subparts F and S may apply. These regulations include requirements for initiating and conducting RCRA corrective actions, remediating groundwater, and operating corrective action management units and temporary units associated with remediation operations. In states authorized to implement RCRA, additional state

regulations more stringent or broader in scope than federal requirements must also be addressed.

Most RCRA regulations affecting conventional treatment technologies will not apply to the in-situ metal-enhanced dechlorination technology because once installed, properly designed and maintained systems generate no residual waste. However, during installation activities, the excavation of a trench and removal of soil from the saturated zone is required. Many chlorinated solvents are RCRA "F-listed" wastes; therefore, at sites where groundwater is contaminated with these compounds, soils removed from the saturated zone may also contain F-listed contaminants and be classified as hazardous waste. If so, these soils will require management, including storage, shipment, and disposal, following RCRA guidelines. Active industrial facilities generating hazardous waste are required to have designated hazardous waste storage areas, and most operate under 90-day storage permits. A facility's storage area could be used as a temporary storage area for contaminated soils generated during the installation of the in-situ metal-enhanced dechlorination technology. For nonactive facilities, or those not generating hazardous waste (as in the case of the site where the New York demonstration occurred), a temporary storage area should be constructed on site following RCRA guidelines, and a temporary hazardous waste generator identification number should be obtained from the regional EPA office. Guidelines for hazardous waste storage are listed under 40 CFR parts 264 and 265. Also, water removed from the excavation may require management as a hazardous waste. Tank storage of liquid hazardous waste must meet the requirements of 40 CFR part 264 or 265, subpart J.

The reactive iron may require occasional physical or chemical treatment to remove entrapped solids or precipitates from the reactive iron medium. Portions of the influent side of the reactive iron may be periodically replaced. For in-situ systems, methods for treating or replacing the iron are still under evaluation at the time of this report, and therefore the exact methods that will be used are unknown at this time. If these actions occur, removed water, soil, or reactive iron may be RCRA hazardous wastes, and RCRA requirements for hazardous waste disposal (see 40 CFR parts 264 and 265) may apply. However, iron removed from the aboveground reactor during a previous SITE Program demonstration in New Jersey was tested for residual contamination. The iron was determined to be nonhazardous and did not require

management as a RCRA hazardous waste, and was subsequently sold as scrap metal.

Although not typically required, if secondary treatment is used in conjunction with the in-situ metal-enhanced dechlorination process, additional RCRA regulations may apply. If secondary treatment involves extraction and treatment of groundwater, and the groundwater is classified as hazardous waste, the treated groundwater must meet treatment standards under land disposal restrictions (LDR) (40 CFR part 268) before reinjection or placement on the land (for example, in a surface impoundment).

RCRA parts 264 and 265, subparts AA, BB, and CC address air emissions from hazardous waste treatment, storage, and disposal facilities. These regulations would probably not apply directly to the in-situ metal-enhanced dechlorination technology, but may apply to the overall process if it incorporates secondary treatment, such as air **sparging/SVE**. Subpart AA regulations apply to organic emissions from process vents on certain types of hazardous waste treatment units. Subpart BB regulations apply to fugitive emissions (equipment leaks) from hazardous waste treatment, storage, and disposal facilities that treat waste containing organic concentrations of at least 10 percent by weight. Many organic air emissions from hazardous waste tank systems, surface impoundments, or containers will eventually be subject to the air emission regulations in 40 CFR parts 264 and 265, subpart CC. Presently, EPA is deferring application of the Subpart CC standards to waste management units used solely to treat or store hazardous waste generated on site from remedial activities required under RCRA corrective action or CERCLA response authorities (or similar state remediation authorities). Therefore, Subpart CC regulations may not immediately impact implementation of the in-situ metal-enhanced dechlorination technology or associated secondary treatment technologies used in remedial applications. EPA may remove this deferral in the future.

3.5.3 Clean Water Act

The Clean Water Act (CWA) governs discharge of pollutants to navigable surface water bodies or publicly-owned treatment works (POTW) by providing for the establishment of federal, state, and local discharge standards. Because the in-situ metal-enhanced dechlorination technology does not normally result in extraction and discharge of contaminated groundwater to

surface water bodies or POTWs, the CWA would not typically apply to the normal operation and use of this technology.

3.5.4 Safe Drinking Water Act

The Safe Drinking Water Act (SDWA), as amended in 1986, required EPA to establish regulations to protect human health from contaminants in drinking water. EPA has developed the following programs to achieve this objective: (1) a drinking water standards program, (2) an underground injection control program, and (3) **sole-source aquifer and wellhead protection programs**.

SDWA primary (health-based) and secondary (aesthetic) **MCLs** generally apply as cleanup standards for water that is, or may be, used as drinking water. In some cases, such as when multiple contaminants are present, more stringent MCL goals may be appropriate. During the SITE demonstration, the in-situ metal-enhanced dechlorination process's performance was evaluated to determine its compliance with SDWA MCLs and NYSDEC standards for several critical VOCs. The results indicated that effluent concentrations met MCLs during all months of testing after system performance stabilized; four out of 90 critical parameter measurements slightly exceeded NYSDEC limits in the same period.

Water discharge through injection wells is regulated by the underground injection control program. The technology does not require extraction and reinjection of groundwater; therefore, regulations governing underground injection programs would not typically apply to this technology.

The sole-source aquifer and **wellhead protection programs** are designed to protect specific drinking water supply sources. If such a source is to be remediated using the in-situ metal-enhanced dechlorination technology, appropriate program officials should be notified, and any potential regulatory requirements should be identified. State groundwater antidegradation requirements and water quality standards (WQS) may also apply.

3.5.5 Clean Air Act

The Clean Air Act (CAA), as amended in 1990, regulates stationary and mobile sources of air emissions. CAA regulations are generally implemented through combined federal, state, and local programs. The CAA includes pollutant-specific standards for major stationary sources

that would not be ARARs for the in-situ metal-enhanced dechlorination process, and would apply only if auxiliary treatment (such as air sparging/SVE) were employed. State and local air programs have been delegated significant air quality regulatory responsibilities, and some have developed programs to regulate toxic air pollutants (EPA 1989). Therefore, state air programs should be consulted regarding secondary treatment if used in conjunction with this technology.

3.5.6 Mixed Waste Regulations

Use of the in-situ metal-enhanced dechlorination technology at sites with radioactive contamination might involve treatment of mixed waste. As defined by the Atomic Energy Act (AEA) and RCRA, mixed waste contains both radioactive and hazardous waste components. Such waste is subject to the requirements of both acts. However, when application of both AEA and RCRA regulations results in a situation that is inconsistent with the AEA (for example, an increased likelihood of radioactive exposure), AEA requirements supersede RCRA requirements (EPA 1988a). OSWER, in conjunction with the Nuclear Regulatory Commission (NRC), has issued several directives to assist in identification, treatment, and disposal of low-level radioactive mixed waste. Various OSWER directives include guidance on defining, identifying, and disposing of commercial, mixed, low-level radioactive, and hazardous waste (EPA 1988b). If the in-situ metal-enhanced dechlorination process is used to treat groundwater containing low-level mixed waste, these directives should be considered, especially regarding contaminated soils excavated during installation. If high-level mixed waste or transuranic mixed waste is treated, internal DOE orders should be considered when developing a protective remedy (Department of Energy [DOE] 1988). The SDWA and CWA also contain standards for maximum allowable radioactivity levels in water supplies.

3.57 Occupational Safety and Health Act (OSHA)

OSHA regulations in 29 CFR parts 1900 through 1926 are designed to protect worker health and safety. Both Superfund and RCRA corrective actions must meet OSHA requirements, particularly § 19.10.120, Hazardous Waste Operations and Emergency Response. Part 1926, Safety and Health Regulations for Construction, applies to any

on-site construction activities. For example, excavation of the trench for placement of the reactive iron medium during the demonstration was required to comply with regulations in 29 CFR part 1926, subpart P. Any more stringent state or local requirements must also be met. In addition, health and safety plans for site remediation projects should address chemicals of concern and include monitoring practices to ensure that worker health and safety are maintained.

3.6 State and Community Acceptance

State regulatory agencies will likely be involved in most applications of the metal-enhanced dechlorination process at hazardous waste sites. Local community agencies and citizen's groups are often also actively involved in decisions regarding remedial alternatives.

Because few applications of the metal-enhanced dechlorination technology have been completed, limited information is available to assess long-term state and community acceptance. However, state and community acceptance of this technology is generally expected to be high, for several reasons: (1) relative absence of intrusive surface structures that restrict use of the treatment area; (2) absence of noise and air emissions; (3) the system is capable of significantly reducing concentrations of hazardous substances in groundwater; and (4) the system generates no residual wastes requiring off-site management and does not transfer waste to other media.

NYSDEC oversees investigation and remedial activities at the New York site. State personnel were actively involved in the preparation of the work plan for the demonstration of the pilot-scale funnel and gate system and monitored system construction and performance. NYSDEC will also be actively involved in planning for any full-scale systems installed at the site. The role of states in selecting and applying remedial technologies will likely increase in the future as state environmental agencies increasingly assume many of the oversight and enforcement activities previously performed at the EPA Regional level. For these reasons, state regulatory requirements that are sometimes more stringent than federal requirements may take precedence for some applications. Also, as risk-based closure and remediation become more commonplace, site-specific cleanup goals determined by state agencies will drive increasing numbers of remediation projects, including applications involving the metal-enhanced dechlorination technology.

Section 4 Economic Analysis

This economic analysis presents cost estimates for using an in-situ application of the metal-enhanced dechlorination technology to treat contaminated groundwater. Costs are presented for two full-scale options: 1) a continuous, reactive iron wall; and 2) a funnel and gate system. The cost estimates are based on systems designed to treat the types and concentrations of chlorinated VOCs observed at the New York demonstration site. The estimates are based on data compiled during the SITE demonstration and from additional information obtained from ETI, S&W, current construction cost estimating guidance, independent vendors, and SITE Program experience.

Past studies by ETI have indicated that costs for this technology are highly variable and are dependent on the types and concentrations of the contaminants present, dimensions of the contaminant plume, site hydrogeology, regulatory requirements, and other site-specific factors. Estimates for total cost and cost per gallon of water treated are also heavily influenced by assumptions regarding the duration of the treatment program and the cumulative volume treated. Furthermore, it is important to note that the cost data presented in this report are partially based on extrapolations from design and operating parameters for the pilot-scale system evaluated during the SITE demonstration. The purpose of the pilot-scale system was to determine the optimal design and operating parameters for a full-scale system. Differences between the capabilities of New York pilot-scale system and full-scale systems designed for optimal performance at other sites could cause actual costs to vary significantly from estimates presented in this report.

Cost data are presented in terms of total cost and cost per gallon of water treated to facilitate comparison of costs with other treatment technologies. However, for passive in-situ systems, the cumulative volume treated is limited by the natural groundwater flow velocity, and cost per gallon may not always reflect the technology's overall

value. The in-situ metal-enhanced dechlorination process combines the ability to remediate groundwater with features typically associated with containment systems; under optimal operating conditions, the technology prevents migration of contaminated groundwater toward potential receptors by treating water passing through it. The technology could be combined with source reduction activities to enhance an overall remedial program at a site.

Due to the many factors that potentially affect the cost of using this technology, several assumptions were necessary to prepare the economic analysis. Several of the most significant of these assumptions are: (1) a continuous, reactive iron wall is assumed to be best-suited for this particular application; however, cost estimates for a funnel and gate system are also provided for comparison; (2) the system will treat water contaminated with TCE, cDCE, and VC at concentrations observed during the SITE demonstration; and (3) the system will treat groundwater for 20 years. (This assumption requires extrapolation of some SITE demonstration data to the longer operating period.)

The 20-year timeframe was selected for consistency with cost evaluations of other innovative technologies evaluated by the EPA SITE Program, and because it facilitates comparison to typical costs associated with conventional, long-term remedial options. The timeframe does not reflect any estimate of the actual time required to remediate groundwater at the New York site.

This section summarizes site-specific factors that influence costs, presents assumptions used in this analysis, discusses estimated costs, and presents conclusions of the economic analysis. Tables 4-1 and 4-2 present the estimated costs generated from this analysis. Costs have been distributed among 12 categories applicable to typical cleanup activities at Superfund and RCRA sites (Evans 1990). Costs are presented in 1996 dollars, are rounded to

Table 4-1. Estimated Costs Associated with the Metal-Enhanced Dechlorination Technology: Continuous Wall System

Cost Category	cost	Total Cost
Site Preparation^b		\$268,600
Administrative	\$15,700	
Treatability study	20,000	
System design	10,000	
Excavation and backfill	152,500	
Monitoring wells	6,100	
Soil and Water Disposal	64,300	
Permitting and Regulatory^b		4,000
Mobilization and Startup^b		40,000
Capital Equipment ^c		143,000
Reactive Iron	135,000	
Sampling Equipment	8,000	
Demobilization^b		\$11,000
Total Estimated Fixed Costs		\$466,600
Labor (Sampling and Routine O&M)		\$5,500
Supplies ^d		2,000
PPE	\$300	
Carbon Canisters	700	
Sampling equipment	1,000	
Utilities ^e		0
Effluent Treatment and Disposal ^f		0
Residual Waste Handling ^f		0
Analytical Services ^f		9,300
Equipment Maintenance^{e,d}		4,100
Total Estimated Variable (Annual) Costs		\$20,900
Total Estimated Fixed and Variable Costs After 20 Years ^e		\$884,600
Costs per 1,000 gallons treated^f		\$18.02
Costs per gallon treated^f		\$0.018

Notes:

- All costs presented in 1996 dollars.
- ^a Costs estimated based on data from SITE demonstration and other sources.
- ^b Fixed costs.
- ^c Variable costs, presented as annual total.
- ^d Annual total prorated from expense incurred at 7-year intervals.
- ^e Total costs after 20 years of operations; all annual costs multiplied by 20, plus total fixed costs.
- ^f Total of 49.1 million gallons of groundwater treated.

Table 4-2. Estimated Costs Associated with the Metal-Enhanced Dechlorination Technology: Funnel and Gate System

Cost Category	cost	Total Cost
Site Preparation^b		\$382,100
Administrative	\$15,700	
Treatability study	20,000	
System design	10,000	
Funnel and Gate Construction	266,000	
Monitoring wells	6,100	
Soil and Water Disposal	64,300	
Permitting and Regulatory^b		4,000
Mobilization and Startup^b		32,500
Capital Equipment^b		143,000
Reactive Iron	135,000	
Sampling Equipment	8,000	
Demobilization^b		\$11,000
Total Estimated Fixed Costs		\$572,600
Labor (Sampling and Routine O&M)		\$5,500
Supplies ^c		2,000
PPE	\$300	
Carbon Canisters	700	
Sampling equipment	1,000	
Utilities^c		0
Effluent Treatment and Disposal ^c		0
Residual Waste Handling ^c		0
Analytical Services ^c		9,300
Equipment Maintenance ^{c,d}		2,700
Total Estimated Variable (Annual) Costs		\$19,500
Total Estimated Fixed and Variable Costs After 20 Years^e		\$962,600
Costs per 1,000 gallons treated^f		\$19.60
Costs per gallon treated^f		\$0.020

Notes:

All costs presented in 1996 dollars.

^a Costs estimated based on data from SITE demonstration and other sources.

^b Fixed costs.

^c Variable costs, presented as annual total.

^d Annual total prorated from expense incurred at 7-year intervals.

^e Total costs after 20 years of operations; all annual costs multiplied by 20, plus total fixed costs.

^f Total of 49.1 million gallons of groundwater treated.

the nearest 100 dollars, and are considered to be order-of-magnitude estimates.

4.1 Factors Affecting Costs

Costs for implementing this technology are significantly affected by site-specific factors, including site regulatory status, waste-related factors, and site features. The regulatory status of the site typically depends on the type of waste management activities that occurred on site, the relative risk to nearby populations and ecological receptors, the state in which the site is located, and other factors. The site's regulatory status affects costs by mandating ARAR's and remediation goals that may affect the system design parameters and duration of the remediation project. Certain types of sites may have more stringent monitoring requirements than others, depending on regulatory status.

Waste-related factors affecting costs include contaminant plume size and geometry; contaminant types and concentrations, and regulatory agency-designated treatment goals. Plumes that cover extensive areas will require longer walls or more funnels and gates to achieve hydraulic control, and may take longer to pass through the treatment system. Larger contaminant masses (plume volume times contaminant concentration) require greater amounts of reactive iron.

The contaminant types and concentrations in the groundwater determine contaminant half-lives. The required residence time in the iron, which determines the appropriate width for the reactive iron zone and affects capital equipment costs and construction costs, is based on the contaminant half-lives, the remediation goals, and the groundwater flow velocity. The types of contaminants and the remediation goals may also determine the need for auxiliary in-situ treatment systems and will influence performance monitoring requirements.

Site features affecting costs include site hydrogeology (geologic features and groundwater flow rates), groundwater chemistry (for example, concentrations of inorganic substances), and site location and physical characteristics. Hydrogeologic conditions are significant factors in determining the applicability and design parameters, and thus the costs, of in-situ applications of the metal-enhanced dechlorination process, and should be thoroughly defined before applying this technology. The saturated thickness determines the required height of the

reactive iron wall. The groundwater flow velocity determines the thickness of the iron wall required to allow sufficient residence time for dechlorination to occur. These factors (along with the dimensions of the contaminant plume) determine the necessary volume of iron and trench dimensions. The depth to water and the depth to the uppermost underlying aquitard determine the depth of the installation and the type of construction technology that will be employed. All of these factors affect capital equipment costs and site preparation costs. Also, since this is a passive technology, the groundwater flow velocity and saturated thickness will control volumetric flow through the system, influencing the duration of the remediation project and time-related variable costs, such as analytical and maintenance costs.

Groundwater chemistry can also affect costs. High concentrations of dissolved inorganic substances in **influent** groundwater may result in precipitation of compounds such as calcium carbonate, particularly on the **upper/influent** side of the iron, requiring more frequent maintenance.

Site location and physical features will impact mobilization, demobilization, and site preparation costs. Mobilization and demobilization costs are affected by the relative distances that system materials must travel to the site. Sites requiring extensive **surficial** preparation (such as constructing access roads, clearing large trees, working around or demolishing structures) or restoration activities will also incur higher costs.

Depending on the type of system installed, the availability of existing electrical power and water supplies may facilitate construction activities. However, unlike many conventional technologies, system operation typically requires no utilities. For these reasons, utilities are typically not a significant factor affecting costs for this technology.

4.2 Assumptions Used in Performing the Economic Analysis

This section summarizes major assumptions regarding site-specific factors and equipment and operating parameters used in this economic analysis. Certain assumptions were made to account for variable site and waste parameters. Other assumptions were made to simplify cost estimating for situations that actually would require complex engineering or financial functions. In

general, most system operating issues and assumptions are based on information provided by ETI, S&W, and observations made during the SITE demonstration. Cost figures are established from information provided by ETI (ETI 1996b; 1996d), S&W (1994), current environmental restoration cost guidance (R.S. Means [Means] 1996), and SITE Program experience.

Assumptions regarding site- and waste-related factors include the following:

- The site is a Superfund site, located in the north-eastern U.S.
- Site groundwater is contaminated with TCE, cDCE, and VC at maximum concentrations of about 300 µg/L, 500 µg/L, and 100 µg/L, respectively.
- The cleanup goals are federal MCL requirements of 5 µg/L for both TCE and cDCE, and 2 µg/L for VC.
- The site is located in a rural area, but is easily accessible to standard (wheel-mounted) heavy equipment.
- Contaminated water is located in a shallow aquifer that overlies a dense, silty clay aquitard at a depth of 15 feet bgs.
- The aquifer is a moderately permeable sand and gravel aquifer, with a natural horizontal flow velocity of 0.75 foot per day. The seasonal saturated thickness varies from about 10 to 12 feet.
- The groundwater contaminant plume is 300 feet wide.
- The site has no existing structures requiring demolition and does not require extensive clearing. There are no existing utilities on site that require relocation or restrict operation of heavy equipment such as excavators, cranes, or drill rigs.
- Typical naturally occurring inorganic substances are present in site groundwater, but do not result in excessively rapid precipitate buildup.

Assumptions regarding treatment system design and operating parameters include the following:

- A continuous iron wall will be used for this application. However, costs for an alternative three-gate funnel and gate system are presented for comparison.
- The hydraulic conductivity of the iron is assumed to be 142 feet per day; the porosity is assumed to be 0.4. The groundwater flow velocity through the continuous iron wall is assumed to be about the same as for the natural aquifer materials, 0.75 foot per day. Based on these parameters, the plume dimensions, and the saturated thickness, the wall will be 300 feet long, 12.5 feet high, and 1.0 foot thick, and will require about 337.5 tons of iron (ETI 1996b; 1996d).
- If a funnel and gate system is used, the system would consist of three gates, each about 20 feet wide. Total system length (including sheet pile funnels) would be 440 feet. According to ETI, funnel and gate systems significantly accelerate flow velocities and would treat about the same volume of water and the same contaminant mass flux as the continuous wall. For this reason, ETI estimates that the combined total mass of iron used for the 3 gates would be the same as the minimum recommended for the continuous wall (about 337.5 tons), resulting in each gate having a 5-foot-thick iron wall (ETI 1996d).
- The minimum volume of groundwater that will pass through the continuous wall or through the funnel and gate system during the remediation project is assumed to be 49.1 million gallons, assuming the flow velocity, porosity, and hydraulic conductivity remain constant.
- ETI will provide a representative as an on-site consultant for key phases of the construction.
- The system continually treats groundwater for 20 years. No downtime is required for periodic maintenance.
- The system continues to achieve cleanup goals over the remediation period. For this reason, and because the treatment system operates in-situ, there

are no additional effluent management requirements, such as air sparging.

- After construction, the treatment system operates without the constant attention of an operator. Routine labor requirements consist of monthly sampling, measurement of water levels, inspection of the monitoring wells and ground surface above the system, and mowing the area above the system.
- Periodic maintenance may consist of using soil mixing equipment to agitate the upgradient side of the iron wall every 5 to 7 years. However, the effectiveness and feasibility of this technique is undocumented at this time.
- All system components are below grade, so no antifreezing measures are required.
- All equipment and supplies are mobilized from within 500 miles of the site, or less.
- Monthly samples of upgradient (influent) and downgradient (effluent) groundwater will be required for the first 6 months after installation. After this period, quarterly samples will be required, for 20 years.

Depreciation is not considered in order to simplify presenting the costs of this analysis. Most groundwater remediation projects are long-term in nature, and usually a net present worth analysis is performed for cost comparisons. However, the variable costs for this technology are relatively low, and no other system configurations or technologies are presented in this analysis for comparison. For these reasons, annual costs are not adjusted for inflation, and no net present value is calculated.

4.3 Cost Categories

Table 4-1 presents cost breakdowns for each of the 12 cost categories for the continuous wall. Data have been presented for the following cost categories: (1) site preparation, (2) permitting and regulatory, (3) mobilization and startup, (4) capital equipment, (5) labor, (6) supplies, (7) utilities, (8) effluent treatment and disposal, (9) residual waste shipping and handling, (10) analytical services, (11) equipment maintenance, and (12) site demobilization.

Because costs for a funnel and gate system would probably be different than those associated with a continuous wall, Table 4-2 presents the costs for a three-gate funnel and gate system treating the same size and type of contaminant plume as the continuous wall. Each of the 12 cost categories are discussed below.

4.3.1 Site Preparation Costs

Site preparation costs include administration costs, costs for conducting a bench-scale treatability study, conducting engineering design activities, and preparing the treatment area. Site preparation also includes costs associated with constructing the continuous wall or funnel and gate system and making the system operational, with the exception of mobilization charges for specialized heavy construction equipment (see Section 4.3.3) and the cost of the iron medium (see Section 4.3.4).

Administrative costs include costs for legal searches, contracting, and general project planning activities. Administrative costs are highly site-specific; for this estimate, administrative costs are assumed to be \$12,500, or about 200 hours of technical staff labor at \$50 per hour and 100 hours of administrative staff labor at \$25 per hour (Means 1996). Also, ETI typically charges a site license fee equal to 15 percent of the iron costs (see Section 4.3.4). For either the full-scale continuous wall or funnel and gate systems, ETI's site license fee is estimated to be about \$3,200.

According to ETI and S&W, a phased treatability study will take between 2 to 4 months to complete (see Section 5 for a discussion of the four phases used to implement the technology). Treatability study costs include expenses for column tests and labor. According to ETI, typical analytical laboratory costs for column tests for a project similar to the one at this site will be about \$15,000. The labor for the treatability study will be about \$5,000, inclusive of 100 hours at an average rate of \$50 per hour. The total cost of a treatability study will be about \$20,000 (EPA 1997).

After the study and a site assessment, ETI will assist in the design of an optimal system configuration for a particular site. The total system design costs are estimated to be about \$10,000. This cost includes about 130 labor hours at an average rate of \$75 per hour (Means 1996). This estimate assumes that site hydrogeology has already been

thoroughly characterized, and no additional hydrogeologic data will be required. If additional hydrogeologic studies are required, design costs could be higher.

Treatment area preparation costs depend on the type of system used. ETI estimates that for a site having the same waste and site features as the New York site, a continuous reactive iron wall may be the most cost effective type of system (ETI 1996d). Costs for a continuous wall include excavating a trench, backfilling it with reactive iron, disposing of the displaced soil, and installing a groundwater monitoring system. This estimate assumes that a continuous trenching/backfill technique will be used to excavate the trench and emplace the iron, eliminating the need for shoring. Before excavating the trench, soil from above the saturated zone (this estimate assumes the upper 3 feet of native soil) can be excavated with a conventional backhoe, stockpiled on site, and eventually replaced to form a cover over the iron, at an assumed cost of about \$2,000 (Means 1996).

After the top 3 feet of soil are removed, the trench will be extended down to the top of the underlying clay layer, in this case assumed to be 15 feet below ground surface, using continuous trenching/backfilling equipment. The equipment will continuously excavate and backfill each section of trench with iron, up to about 2.5 feet below grade, continuing until the 300-foot long iron wall is completed. According to ETI, at this depth, it is possible to construct about 100 to 200 lineal feet of reactive iron wall per day using this technique. Costs for the excavation/backfill equipment and operator are estimated to be \$150,500, not including mobilization (see Section 4.3.3). (This figure includes costs for transferring soil to roll-off boxes as the trench is excavated.) Total trench construction costs are estimated to be \$152,500, not including the costs of the reactive iron (see Section 4.3.4) (Means 1996; ETI 1996d).

After all of the iron is emplaced and settled, the top of the wall will be about 3 feet bgs. The stockpiled native soil from the upper part of the excavation, which will not have contacted contaminated groundwater, will be used to fill the upper part of the trench. Soil excavated from the lower portion of the trench (below the water table) will have contacted groundwater contaminated with RCRA F-listed solvents and may require management as a hazardous waste. This cost estimate assumes that the soil will be loaded into roll-off containers, stored on site pending characterization, and shipped offsite and disposed of as a hazardous waste. Based on the dimensions of the trench

for the continuous wall (and the volume of soil displaced by monitoring well construction), about 140 cubic yards of soil will require disposal. Assuming a disposal cost of \$400 per cubic yard (landfill disposal), transport costs of \$3.30 per mile for each roll-off container, characterization and manifesting fees of \$5000, and disposal at a location 100-miles from the site, total costs for managing this material are estimated to be about \$62,300. Actual costs for waste disposal are highly site specific, and may vary substantially from this estimate, particularly if the soil requires incineration (Means 1996).

Alternatively, if a funnel and gate configuration is used, ETI estimates that a three-gate, 440-foot-long system would capture the 300-foot-wide plume. Each gate would be constructed using the same general techniques used for the pilot-scale system demonstrated at the New York site (see Section 1). Site preparation costs would include costs for excavating and backfilling the three 20-foot-wide gates with a reactive iron section bordered by pea gravel and installing the sheet-piling to form the continuous funnel. ETI estimates construction and material costs (including sheet piling, but not including the reactive iron) to be \$264,000 for this system (ETI 1996d). For estimating purposes, topsoil removal and replacement, soil disposal, and all other site preparation costs are assumed to be the same as for the continuous wall.

A groundwater monitoring system will be required to monitor system performance. For a continuous wall, this estimate assumes that the system will require a well spacing of no more than 50 feet along the downgradient side of the wall, to ensure that all sections of the wall are performing adequately. Three upgradient wells will also be installed to allow determination of the system's removal efficiency. Installation and development of nine, 15-foot-deep PVC monitoring wells with locking caps and flush-mounted protective casings will be required. The assumed cost for these wells is \$45 per foot (including drill rig mobilization from within 50 miles of the site), for a total cost of about \$6,100. Auger cuttings (about 2 cubic yards) will be disposed of with the material from the trench; costs for this were included in the waste disposal costs previously discussed.

For a funnel and gate system, this estimate assumes that one upgradient well and two downgradient wells would be constructed in the pea gravel zones at each gate. It may be possible to install these wells at the time of construction, eliminating the need for drilling. However, at a minimum, the wells will require bracing and completion methods

similar to those used during the SITE demonstration, so for estimating purposes, construction costs for these wells are also assumed to be \$45 per lineal foot, for a total of \$6,100.

Water from monitoring well development (or from trench dewatering activities for a funnel and gate system) will contain site contaminants. This estimate assumes that the water can be passed through a carbon filter and discharged to the ground surface upgradient from the system. Costs for this method of disposal are assumed to be about \$2,000, including the cost of carbon canisters and labor.

All system components will be completed below grade. The wells will have locking inner caps. For this reason, no costs for additional security (fences) will be incurred.

For a continuous iron wall, total site preparation costs are estimated to be \$268,600; for a funnel and gate system, site preparation costs are assumed to be \$382,100.

4.3.2 Permitting and Regulatory Costs

Permitting and regulatory costs are highly site-specific and will depend on whether treatment is performed at a Superfund or a RCRA corrective action site; wellhead protection area restrictions; and other factors. Superfund site remedial actions must be consistent with ARARs of environmental laws, ordinances, regulations, and statutes, including federal, state, and local standards and criteria. Remediation at RCRA corrective action sites requires additional monitoring and record keeping, which can increase the base regulatory costs.

The cost of all permits is based on the effluent characteristics and related receiving water requirements. For this analysis, groundwater is not extracted before treatment, so the costs assume that no permit for discharge of treated effluent to the aquifer will be required. (This assumption is based on ETI's experience at several full-scale installations in the U.S.). For this reason, this estimate assumes that total permitting and regulatory costs are minimal; about \$4,000. This includes 50 hours of labor at \$75 per hour, and \$250 for miscellaneous expenses such as fees and reproduction costs.

4.3.3 Mobilization and Startup Costs

Mobilization and startup costs consist of mobilizing the construction equipment and materials and delivering the reactive iron. However, unlike conventional aboveground

systems, no additional assembly charges are incurred beyond the construction costs described in Section 4.3.1. The technology requires no electrical power, water supply, or other utilities. For in-situ applications of this technology, mobilization and startup costs are assumed to consist solely of equipment mobilization charges. Mobilization costs will vary depending on the location of the site in relation to suppliers. Based on information provided by ETI, mobilization of the specialized construction equipment for a continuous wall (to a site in the northeastern U.S.) is assumed to be \$40,000. For a funnel and gate system, equipment mobilization is assumed to be \$32,500.

For the site where the demonstration of the aboveground reactor occurred, which was also in the northeastern U.S., ETI estimated that iron transportation costs would be about \$75 per ton, or about 14 percent of the cost of the iron (EPA 1997). ETI's current estimates for the cost of the iron include delivery costs (see Section 4.3.4); for this reason, iron delivery charges are not listed as a separate item in Tables 4-1 and 4-2. However, costs for the iron will be influenced by the site's location in relation to the supplier, the distance the iron must be transported to the site, the mode of packaging (bulk, drums, or 1-cubic yard "totes"), and the mode of transportation. For this reason, iron costs may vary on a site-specific basis.

4.3.4 Capital Equipment Costs

Capital equipment costs for this analysis include the cost of the reactive iron and groundwater monitoring equipment. Costs for other materials (monitoring wells, sheet piling funnels, etc.) were previously discussed in Section 4.3.1 and are not considered to be capital equipment costs for this estimate.

ETI configures the complete treatment system based on site-specific conditions. According to ETI, current costs for the reactive iron, including delivery to a site in the northeastern U.S., are about \$400 per ton, assuming truck delivery of iron in bulk form. (However, costs may vary on a site-specific basis.) ETI estimates that the typical iron density after settling is about 180 pounds per cubic foot (0.09 ton per cubic foot). Based on this estimate, the 3,750-cubic-foot continuous wall will require about 337.5 tons of reactive iron, resulting in a total capital equipment cost of about \$135,000. According to ETI, the same amount of iron would be required for a funnel and gate

system, as the system would treat the same volume of contaminated groundwater as the continuous wall.

For either system, equipment that will be required to monitor the technology's performance includes a low-flow sampling pump and meters to measure pH, Eh, and other field parameters. Because this is a long-term project purchasing these items will probably be more cost effective than renting them. This estimate assumes that these items will cost about \$8,000.

Total capital equipment costs are estimated to be \$143,000 for either the continuous wall or the funnel and gate system.

4.3.5 Labor Costs

Once the system is functioning, it is assumed to operate unattended and continuously except during routine O&M, monitoring, and sampling activities.

Routine O&M will generally consist of mowing the area over and around the treatment system (to prevent establishment of deep-rooted plants and maintain access to the monitoring wells), inspecting the area for excessive subsidence or erosion, and inspecting the condition of the monitoring wells. Mowing could be contracted out at \$50 per job, and would be required four times per year for an annual cost of \$200.

Inspection activities could be performed concurrently with sampling. This cost estimate assumes that samples will be collected monthly for the first 6 months after installation, and then quarterly for the duration of the project. More frequent monitoring is recommended immediately after installation to ensure that the system is performing according to design. This cost estimate assumes that all sampling and analytical tasks will be performed by independent contractors and labor costs for sampling are \$45 per hour (Means 1996). During each sampling event, sampling personnel should also inspect the general condition of the treatment system area and the condition of the monitoring wells. Routine monitoring and sampling activities are assumed to take about 16 hours per event, assuming measurement of water levels and collection of groundwater samples from nine monitoring wells, laboratory coordination, and sample shipment. Data interpretation and reporting will take an additional 12 hours per event. Based on these estimates total sampling-related labor costs are \$1,260 per sampling event. For a

20-year remediation project, estimated sampling labor costs prorate to about \$5,300 per year.

Total routine O&M and sampling costs are estimated to be \$5,500 per year. Laboratory analytical costs are presented in Section 4.3.10, Analytical Services Costs. Other labor requirements for periodic equipment maintenance (iron replacement) and demobilization are presented in Section 4.3.11, Equipment Maintenance Costs and Section 4.3.12, Site Demobilization Costs.

4.3.6 Supply Costs

Necessary supplies as part of the overall groundwater remediation project include Level D disposable personal protective equipment (PPE) and sampling and field analytical supplies.

Disposable PPE typically consists of latex inner gloves, nitrile outer gloves, and safety glasses. This PPE is used during sampling activities. Disposable PPE is assumed to cost about \$300 per year for the sampler.

Water purged from the upgradient monitoring wells during sampling activities should be contained. Based on the well dimensions, purging the upgradient wells will generate about 15 gallons of water per sampling event. This cost estimate assumes that the water could be pumped through a carbon filter at the completion of each sampling event and discharged to the ground surface upgradient from the system. This estimate assumes that carbon canisters will require replacement annually, at a cost of \$700 each, including disposal/regeneration of the spent carbon (Means 1996). If this is not feasible, additional off-site disposal costs may be incurred. Because detectable concentrations of contaminants are not anticipated to be present in water downgradient from the system, this estimate assumes that water purged from the downgradient wells can be discharged to the ground surface.

Sampling supplies consist of sample bottles, shipping containers, pump hoses or tubing, buckets or drums to temporarily contain purge water, field meter calibration solutions, and other typical groundwater sampling supplies. The numbers and types of necessary sampling supplies are based on the analyses to be performed. For this analysis, annual sampling supply costs are assumed to be \$1,000 (Means 1996).

Total annual supply costs are estimated to be \$2,000.

4.3.7 Utility Costs

The in-situ metal-enhanced dechlorination system typically requires no utilities.

4.3.8 Effluent Treatment and Disposal costs

This estimate assumes that the technology will reduce groundwater contaminants to acceptable levels by in-situ treatment. For this reason, no additional effluent treatment and disposal costs will be incurred.

4.3.9 Residual Waste Shipping and Handling Costs

Based on existing data, it appears that the dechlorination process generates no residual wastes. This estimate assumes that periodic maintenance to restore the iron's hydraulic conductivity (see Section 4.3.11) will be accomplished using in-situ soil mixing or a similar process, and will not result in the generation of soil and iron that requires management as a potentially hazardous waste.

4.3. IO Analytical Services Costs

Analytical services costs include costs for laboratory analyses, data reduction, and QA/QC. Required sampling frequencies, number of samples, and associated QA/QC requirements are highly site-specific and are based on regulatory status, treatment goals, influent contaminant concentrations, areal extent of the contaminant plume (which determines the length of the iron wall or number of gates), and other factors.

This analysis assumes that the number and frequency of samples would be the same for either a continuous wall or funnel and gate system; both cases assume that three background wells and six downgradient wells will be sampled during each event. All of the samples will be analyzed for VOCs to directly monitor system performance. The one background well and two downgradient wells nearest the center of the wall will be monitored for additional parameters to track inorganic precipitation in the iron; bicarbonate alkalinity and metals including calcium, magnesium, and iron, in addition to VOCs. Based on typical costs for these analyses incurred during the New York demonstration, costs for the VOC,

metals, and bicarbonate analyses are assumed to be \$150/sample, \$100/sample, and \$15/sample, respectively. Analytical costs also assume that one trip blank, one matrix spike, and one matrix spike duplicate sample will be submitted for VOC analyses during each event. Geochemical parameters (pH, Eh, DO, conductivity, and temperature) will be measured by sampling personnel in the field using portable meters.

Assuming the sampling frequency discussed in Section 4.3.4 (monthly for the first six months and quarterly thereafter) a total of 84 sampling events will be performed over the 20-year project. Analytical costs for these events prorate to about \$9,000 annually.

Core samples of the reactive iron should be collected periodically and analyzed to evaluate precipitate buildup. This estimate assumes that one sample will be collected bi-annually from the upgradient (influent) side of reactive iron, and analyzed using wet chemistry techniques and by microscopy. This estimate assumes that this sample could be collected during routine sampling activities, and that the analyses would cost about \$600 per sample, prorating to \$300 per year.

Total annual analytical services costs are estimated to be \$9,300.

4.3.7.1 Equipment Maintenance Costs

Long-term data regarding the useful life of the reactive iron are not available. ETI estimates that the iron may last up to several decades, provided it does not become coated or blocked with precipitates. Periodic maintenance may be required to agitate the influent (upgradient) side of the iron to loosen precipitates, which tend to concentrate in the first few inches of reactive iron. It is also possible that the iron may need to be periodically replaced, if maintenance techniques can not successfully loosen precipitate buildup. The timeframe for maintenance or replacement will vary depending on flow rate, groundwater chemistry, and other factors (Focht, Vogan, and O'Hannesin 1996)

This cost analysis assumes that the reactive iron will not require replacement, but will require maintenance every 7 years to maintain flow through the system, or twice during the 20-year project. According to ETI, this may be accomplished using augers or in-situ soil mixing equipment to agitate the influent face of the reactive iron and loosen precipitates. However, this technique has not

been attempted in a field setting, and therefore its feasibility and effectiveness are currently undemonstrated. For this reason, actual costs to perform iron maintenance are unknown.

Based on mobilization and operating costs typically associated with highly-specialized heavy equipment, for each maintenance event labor, equipment mobilization, decontamination, and operating costs for iron maintenance are assumed to be equal to about 30 percent of the original iron costs, or \$40,500, for the continuous wall. Costs are assumed to be slightly less, equal to about 20 percent of the original iron costs, or \$27,000, for the funnel and gate system due to the shorter total length of the reactive iron gates (Focht, Vogan, and O'Hannesin 1996; Means 1996). Assuming that iron maintenance will be required twice during the remediation project, estimated annual iron restoration costs prorate to about \$4,100 for the continuous wall and \$2,700 for the funnel and gate system, but could vary significantly from these estimates, particularly if portions of the iron need to be replaced. Also, if it is necessary to remove monitoring wells to provide clear access to the upgradient side of the iron, additional well replacement costs may be incurred.

4.3.72 Site Demobilization Costs

Site demobilization includes removal of the reactive iron; site cleanup and restoration; and off-site transportation and disposal of the spent iron. Excavation and removal of the iron could be accomplished with a conventional backhoe. This estimate assumes that the iron is non-hazardous and will bear a recycling credit of 3-5 percent of its original value (about \$4,000 to \$7,000). Based on these assumptions, no net costs for removal of the iron are incurred. Backfill of the trench would be completed using a backhoe and clean fill, at a cost of about \$10 per cubic yard. The nine monitoring wells would be removed and the boreholes grouted to the ground surface at a cost of \$20 per foot, for a total cost of about \$3,000. Based on these assumptions, net total iron removal and trench backfill costs are assumed to be about \$5,000 after the iron recycling credit.

For the three-gate funnel and gate system, the iron would be removed and recycled, and the sheet piling would also be removed and hauled away as scrap, assuming it is non-hazardous. The monitoring wells would be removed and disposed of as non-hazardous demolition debris. The gate areas would be brought to grade with clean fill. Net total

costs for removal of the system and backfill for the funnel and gate system are assumed to be the same as for the continuous wall, after recycling credits for the iron and sheet piling (\$5,000).

Final site restoration costs may include optional regrading and seeding of the area. These costs are highly site-specific; in this case, costs are assumed to be \$6,000.

Total demobilization and site restoration costs are assumed to be \$11,000 for the continuous wall or for the funnel and gate system. If the iron or sheet piling require management as a hazardous waste, or do not bear the assumed recycling value, demobilization costs could be significantly higher.

4.4 Economic Analysis Summary

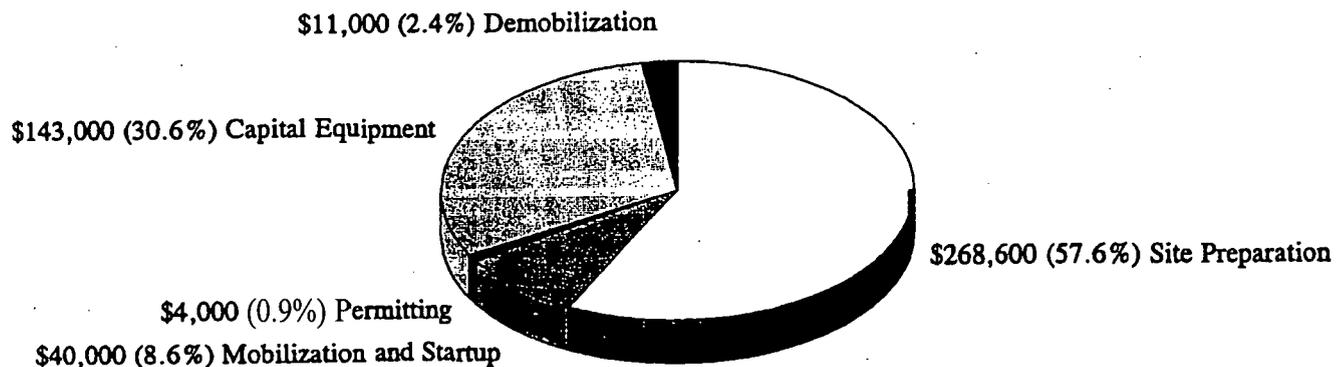
This analysis presents cost estimates for treating groundwater contaminated with TCE, cDCE and VC. Two options are discussed; a continuous reactive wall, and a three-gate funnel and gate system. Operating assumptions include treating a minimum saturated thickness of 10 feet of groundwater flowing at a rate of 0.75 foot per day through a continuous wall, or 3.75 feet per day for a funnel and gate system. Table 4-1 shows the estimated costs associated with the 12 cost categories presented in this analysis for the continuous wall. Table 4-2 shows the estimated costs for the funnel and gate system. Costs were not adjusted for inflation.

For the continuous wall, total fixed costs are estimated to be about \$466,600. Site preparation costs comprise about 57.6 percent of the total fixed costs; capital equipment accounts for about 30.6 percent of the fixed costs. Figure 4-1 shows the distribution of fixed costs for the continuous wall. Total annual variable costs are estimated to be about \$20,900. Analytical services (excluding sampling labor) comprise about 44.5 percent of the variable costs; labor (sampling and ordinary O&M) costs account for about 26.3 percent of these costs. The variable costs also include estimated costs for iron maintenance activities assumed to be required twice during the 20-year project; distributed over the 20-year timeframe these costs account for about 19.6 percent of the annual variable costs. Figure 4-2 shows the distribution of annual variable costs for the continuous wall.

After operating for 20 years, the total fixed and variable costs for the continuous wall remediation scenario

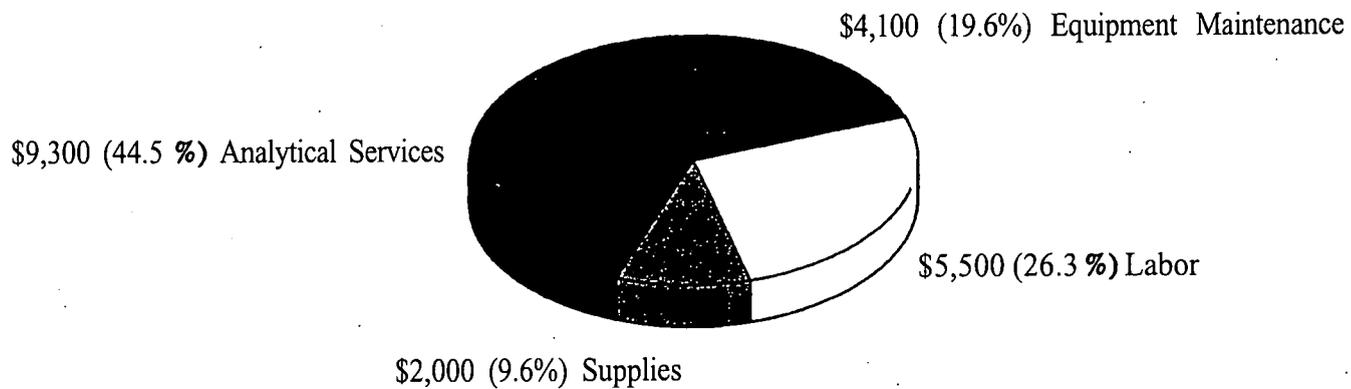
presented in this analysis are estimated to \$884,600. A minimum of about 49.1 million gallons of groundwater would be treated over this time period, assuming flow velocities remain constant at 0.75 foot per day, and the porosity and hydraulic conductivity of the entire wall remain unchanged. Based on these criteria, the total cost per 1,000 gallons treated is about \$18.02, or about 1.8 cents per gallon.

Figures 4-3 and 4-4 exhibit breakdowns of the estimated fixed and variable costs associated with the funnel and gate system, respectively. As shown on Figure 4-3, the major differences between the costs for the continuous wall and the funnel and gate system are in the site preparation portion of the fixed costs. Although fixed costs for the funnel and gate system are considerably higher, higher maintenance costs are assumed to be required for the continuous wall due to the greater length of iron wall that will require maintenance. For this reason, the estimated cost per gallon of groundwater treated for the funnel and gate system (about 2 cents) is only slightly higher than for the continuous wall. The volume of groundwater treated is assumed to be the same in both cases. However, the actual amount of groundwater that would pass through the funnel and gate system would depend on the degree to which the system can accelerate the natural groundwater flow velocity, and therefore may differ from the amount that would pass through a continuous wall. For this reason, and other reasons previously discussed, actual costs may vary significantly from estimates presented in this report.



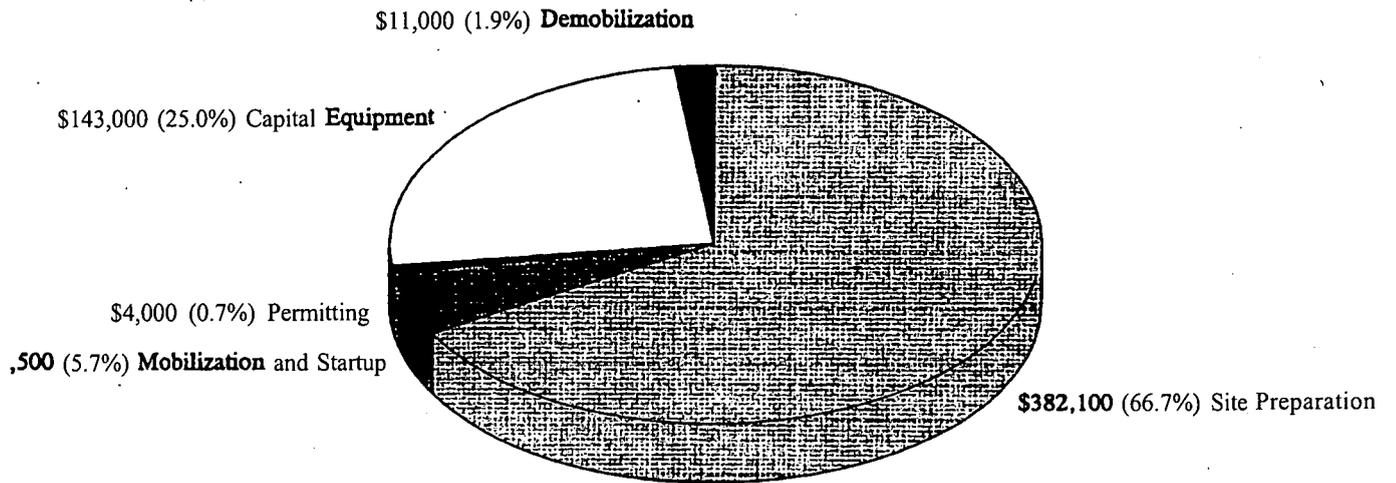
Total Fixed Costs are estimated to be \$466,600.

Figure 4-1. Distribution of fixed costs for continuous wall.



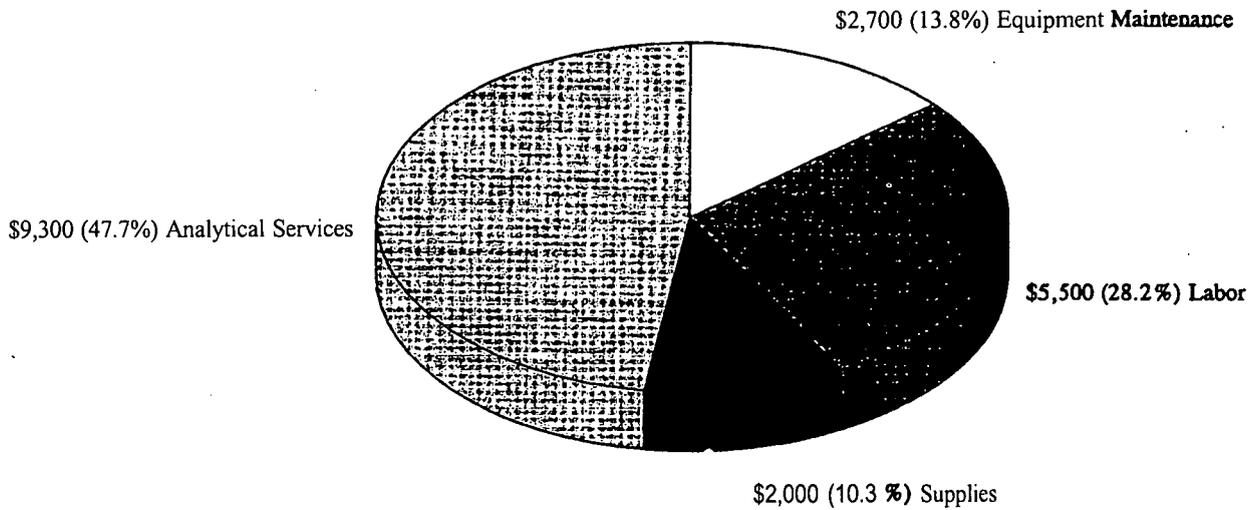
- Notes: 1) Total Annual Variable Costs are estimated to be \$20,900.
 2) Routine sampling and O&M labor; does not include iron restoration.

Figure 4-2. Distribution of annual variable costs for continuous wall.



Total Fixed Costs are estimated to be \$570,600.

Figure 4-3. Distribution of fixed costs for funnel and gate system.



- Notes: 1) Total **Annual** Variable Costs are estimated to be \$19,500.
 2) Routine sampling and O&M labor; does not include iron restoration.

Figure 4-4. Distribution of annual variable costs for funnel and gate system.

Section 5

Technology Status and Implementation

ETI has completed several bench-scale studies, five pilot-scale tests using aboveground reactors and in-situ reactive walls, and six full-scale installations of in-situ systems. Several other field tests of in-situ installations are planned for the near future in Massachusetts and Hawaii. ETI is completing cooperative research and development/licensing arrangements with several U.S. and multinational industrial firms.

The in-situ implementation of the technology involves installing a permeable treatment wall of coarse-grained iron medium across the groundwater plume. The iron degrades chlorinated VOCs as they migrate through the wall under naturally occurring groundwater flow conditions. When the in-situ metal-enhanced dechlorination technology is applied to treat a large plume of contaminated groundwater, impermeable sheet piles or slurry walls may be used to funnel contaminated groundwater through smaller permeable treatment sections, known as gates. Selection of the appropriate type of system depends on site-specific factors.

The metal-enhanced dechlorination process also may be employed aboveground. Aboveground treatment units are designed to treat extracted groundwater. Aboveground treatment units can be available as trailer-mounted transportable units or permanent installations. The configuration of the aboveground units may include a single unit or several units connected in series or in parallel.

The metal-enhanced dechlorination technology is implemented through a four-phase approach. A site data assessment is conducted during phase 1; a feasibility evaluation involving bench-scale testing (and pilot-scale testing if necessary) is conducted during phase 2; system design, costing, and construction occurs during phase 3; and phase 4 involves long-term performance monitoring. Phases 1 and 2 may take about 2 to 4 months, and phase 3

may take about 6 months. The duration of phase 4 will depend on site-specific conditions and regulatory requirements. The phases are described in subsequent sections.

Phase 1 - Site Data Assessment

The purpose of a site data assessment is to review existing data to evaluate site conditions that may affect the performance of the technology. On the basis of this review, the site may be placed into one of two categories. The first category includes sites with a physical setting and groundwater chemistry similar to other sites at which the metal-enhanced dechlorination technology has been shown to be effective. Therefore, implementation of phase 2 (a feasibility evaluation) is not necessary before phase 3 activities begin.

The second category includes sites with unique physical and geochemical properties that may affect the application of the metal-enhanced dechlorination technology. The probability for the successful application of the technology at these sites is unknown, due to the presence of untested chemicals, unusual inorganic chemistry, or unusual geologic settings. For these sites, implementation of phase 2 activities is needed before phase 3 activities can begin. Data that are necessary to assess a site include:

- **Groundwater inorganic and organic chemistry:** The inorganic chemistry of groundwater is important because it indicates whether metals can precipitate during treatment. The effect of metal precipitation on the performance of the technology is discussed in Section 3.1.1. The nature of organic contaminants present in groundwater determines the applicability of the technology to a particular site, as discussed in Section 3.1.1.

- **VOC characteristics:** The technology is appropriate for treating chlorinated methanes, some ethanes, and ethenes. Each compound and its potential by-products have a half-life. The half-life of each compound and its degradation by-products are critical parameters with regard to residence time when designing a treatment system.
- **Site geology and soils:** The type of materials, depth to water, saturated thickness, and presence of an underlying aquitard are important considerations for the design and implementation of in-situ installations of the metal-enhanced dechlorination technology.
- **Hydrogeological data:** Horizontal gradient, hydraulic conductivity and groundwater flow velocity will affect the performance of the metal-enhanced dechlorination technology because they influence the residence time of groundwater in the reactive wall, which affects the required wall thickness.

Phase 2 - Feasibility Evaluation

If the site is placed into the second category as defined in phase 1, a feasibility evaluation is typically performed. The purpose of phase 2 is to evaluate the efficiency of the metal-enhanced dechlorination technology under simulated groundwater flow conditions, by performing laboratory bench-scale (column) tests using representative groundwater samples collected from the site. Groundwater flow and geochemical models may be used to assist in the feasibility evaluation. Feasibility testing should (1) confirm that the VOCs present are degraded by the process, (2) evaluate the rates of VOC degradation, and (3) evaluate associated inorganic geochemical reactions.

Following successful laboratory bench-scale tests, a pilot-scale field test may be conducted to collect additional data to support full-scale application of the process; however, according to ETI, pilot-scale testing is no longer typically required. Pilot-scale testing may not be required, or may be very limited for sites having contaminant, geochemical, and hydrogeologic characteristics similar to other sites for which ETI has extensive past performance data. However, it is important to note that because the technology is relatively new, state regulatory authorities may still require a pilot-scale study if the technology has not been shown to be effective in that particular state. If pilot-scale

testing is required, the results of the bench-scale studies are used to design the pilot-scale system. The pilot-scale system may be in-situ or aboveground, depending on the potential full-scale application and site conditions. This field test provides data which are readily extrapolated to estimate full-scale costs, long-term performance and operation, and maintenance requirements.

A feasibility evaluation report is prepared to document phase 2 testing results. The report interprets the laboratory data with respect to the site's hydrogeologic characteristics and provides information required for the preliminary design and cost estimating activities performed in phase 3.

Phase 3 - System Design, Costing, and Implementation

Phase 3 is the design, costing, and construction of a full-scale system. The results from phase 2 provide the basis for full-scale design. The half-lives of the chlorinated VOCs present in the groundwater and the half-lives of potential dechlorination by-products, determined through bench-scale testing, and data collected during the pilot-scale testing (if required), are used to confirm the correct volume of iron required to treat the types and concentrations of contaminants present. The full-scale system dimensions are determined based on the total residence time necessary for dechlorination; the flow velocity, and the contaminant plume dimensions. These criteria determine the thickness of the reactive iron wall in an in-situ system. For in-situ systems, hydrogeologic factors such as saturated thickness and plume dimensions will also influence the full-scale system design.

Once the full-scale system design is finalized, the system is constructed. According to ETI, steady state operating conditions are typically achieved by the time about 20 to 30 pore volumes of groundwater has passed through the system (ETI 1994).

Phase 4 - Long-Term Performance Monitoring and Maintenance

Routine performance monitoring and reporting are performed according to regulatory requirements. Performance monitoring includes sampling and analysis of treated groundwater to determine the concentrations of VOCs of concern. Decreases in dissolved metal concentrations indicate formation of insoluble precipitates that may clog the reactive iron medium.

As discussed in Section 3, periodic maintenance may be required to restore the hydraulic conductivity and reactivity of the iron. ETI estimates that for full-scale in-situ systems, these activities may be required every 5 to 10 years.

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Appendix A

Vendor's Claims for the Technology

The metal-enhanced dechlorination technology uses a metal (usually iron) to enhance the abiotic degradation of dissolved halogenated organic compounds. Laboratory-scale and field-scale pilot studies conducted over the past 5 years at the Waterloo Centre for Groundwater Research, University of Waterloo, and at several commercial sites in the U.S., have shown that the process can be used effectively to degrade halogenated methanes, some ethanes, and ethenes over a wide range of concentrations. These studies have shown that:

- The degradation kinetics appear to be pseudo first-order (i.e., the rate of reaction is directly proportional to the concentration of the reactants)
- With few exceptions, no persistent products of degradation have been detected and degradation appears to be complete given sufficient time
- The degradation rates of chlorinated compounds are several orders of magnitude higher than those observed under natural conditions
- The reaction rate is dependent on the surface area of iron available

A.1 Advantages and Innovative Features

- Reactants are relatively inexpensive
- The treatment is passive and requires no external energy source
- Contaminants are degraded to harmless products, rather than being transferred to another medium requiring subsequent treatment, regeneration, or disposal

- The reactive iron is highly persistent with, depending upon the application, the potential to last for several years to decades without having to be replaced
- The process is one of the few that appears to have potential for passive in-situ treatment
- The process degrades a wide range of chlorinated volatile organic compounds, including trichloroethene, tetrachloroethene, cis-1,2-dichloroethene, and vinyl chloride. Preliminary tests suggest that it may be applicable for a wider range of compounds in addition to chlorinated "aliphatic" hydrocarbons.

A.2 Technology Status

The first full-scale in-situ installation of the technology occurred at an industrial facility in California in December 1994. Eleven installations of either pilot or full-scale systems have been completed to date. These in-situ installations and others planned in 1997 will assist in the assessment of the long-term field performance of the technology.

The results collected to date show that the ETI technology could be a highly effective aboveground or in-situ method of remediating waters containing chlorinated aliphatic compounds. An in-situ permeable treatment wall of coarse-grained reactive media installed across the plume will degrade compounds as they migrate through the zone under naturally occurring groundwater flow conditions. By utilizing impermeable sheet piles or slurry walls, a large plume of contaminated groundwater can be funneled through smaller permeable treatment sections.

Appendix B Case Studies

This appendix summarizes several case studies on the use of metal-enhanced dechlorination technology. These case studies involve bench-scale units, pilot-scale units, and full-scale units treating contaminated groundwater. The information available for these case studies ranged from detailed analytical data to limited information on system performance and cost. Results from five case studies are summarized in this appendix.

B.1 Semiconductor Facility, South San Francisco Bay, California

B. 7.7 Project Description

Several studies were performed by EnviroMetal Technologies, Inc. (ETI), using groundwater from a former semiconductor manufacturing site in South San Francisco Bay, California to examine the feasibility of constructing and operating an in-situ permeable wall containing a reactive iron medium to replace an existing pump-and-treat system. Groundwater at this site was contaminated with trichloroethene (TCE), cis- 1,2-dichloroethene (cDCE), vinyl chloride (VC), and Freon 113. Results of laboratory column studies performed by ETI indicated that the concentration of dissolved volatile organic compounds (VOCs) in the groundwater was significantly reduced. Following the laboratory studies, pilot- and full-scale units were installed.

B. 7.2 Results

Pilot-Scale System

An aboveground demonstration reactor containing 50 percent iron by weight and 50 percent sand by weight was installed and operated over a 9-month period. Groundwater was pumped through the demonstration reactor at a flow velocity of 4 feet per day.

The groundwater at the semiconductor facility site was highly mineralized. Although precipitate formation was evident at the influent end of the test reactor, the rate of degradation remained relatively constant over the 9-month test period. The following were the pilot-scale test results:

- TCE, 210 ppb, 1.7-hour half-life
- cDCE, 1,415 ppb, 0.9-hour half-life
- VC, 540 ppb, 4.0-hour half-life

Several other aspects of the metal-enhanced dechlorination process were evaluated during this pilot-scale test, including the following.

- **Metals precipitation** - Inorganic geochemical data collected in the field was used to predict the potential for precipitate formation in the reactive iron material. Operation and maintenance requirements for the full-scale design were based on the evaluation of the metals precipitation data.
- **Hydrogen gas production** - Hydrogen gas may be produced as a consequence of the dissociation of water in the presence of granular iron. Rates of hydrogen gas generation measured in the laboratory (Reardon 1995) were used to evaluate the need for any hydrogen gas collection system in the full-scale application. Based on the evaluation, no need for a hydrogen gas collection system was indicated.
- **Microbial Effects** - Groundwater from within the reactor was sampled for microbial analysis. The results indicated that the microbial population in the reactor was similar to the population observed in untreated groundwater. There was no visual evidence of biomass generation during the test.

Full-Scale System

Based on the pilot-test results, a full-scale in-situ treatment wall was installed in December 1994. The reactive wall was 4 feet thick, 40 feet long, and situated vertically between depths of about 7 feet and 20 feet below ground surface. The 4-foot-thick zone of 100 percent granular iron was installed to achieve a hydraulic residence time of about 4 days to treat VOCs to cleanup standards, based on the estimated groundwater velocity of 1 foot per day. VC required the longest residence time to degrade to cleanup standards. A layer of pea gravel about 1 foot thick was installed on both the upstream and downstream sides of the reactive wall. The reactive wall was flanked by slurry walls to direct groundwater flow towards the reactive iron medium. The construction cost for the reactive wall was about \$225,000. Together with slurry walls, capital costs were about \$720,000.

At the time this report was prepared, minimal data for the full-scale system were available. Monitoring wells were installed near the upstream and downstream faces. Initial results indicate that chlorinated VOCs are being reduced to below regulatory levels. For further details see Yamane et al 1995 and Szerdy and others 1995.

Sources: Yamane and others 1995; Szerdy and others 1995; ETI 1996; Focht, Vogan, and O'Hannesin 1996.

B.2 Canadian Forces Base, Borden, Ontario, Canada

B.2.1 Project Description

In May 1991, a small-scale in-situ field test was initiated at the Borden site to treat groundwater contaminated with TCE and PCE. The source of the contaminant plume at the site was located about 4 meters (m) below ground surface and 1 m below the water table. The plume was about 6.6 feet wide and 3.3 feet thick, with a maximum concentration along the axis of about 250,000 and 43,000 $\mu\text{g/L}$ for TCE and PCE, respectively. An in-situ permeable wall was constructed about 18 feet downgradient from the source. The aquifer material consisted of a medium to fine sand, and the average groundwater velocity was about 0.3 feet per day.

The reactive wall was constructed by driving sheet piling to form a temporary cell 5.2 feet thick and 18 feet long. The native sand was replaced by the reactive iron medium,

consisting of 22 percent iron grindings by weight and 78 percent coarse sand by weight. After the reactive iron medium was installed, the sheet piling was removed, allowing the contaminant plume to pass through the wall.

Rows of multilevel samplers were located 1.6 feet upgradient from the wall, at distances of 1.6 feet and 3.3 feet into the wall, and 1.6 feet downgradient from the wall, providing a total of 348 sampling points.

B.2.2 Results

Samples were collected and analyzed over a five-year monitoring period. There was no apparent change in performance and no maintenance required over the five-year duration of the test. The results indicated that about 90 percent of the TCE and 86 percent of the PCE was removed as the contaminant plume passed through the wall. Amounts of dechlorination by-products (dDCE and cDCE) equivalent to about 2 percent of the original mass of TCE and PCE present in the influent were detected at sampling points within the wall. However, these byproducts also were dechlorinated with further distance through the wall. An observed increase in chloride concentrations in effluent samples indicated that the decline in TCE and PCE concentrations was a consequence of dechlorination processes. Although the effluent did not achieve drinking water standards, based on current knowledge it appears that use of a greater proportion of iron relative to contaminant loading, or use of a more reactive form of iron, could have improved performance. No VC was detected as a result of PCE, TCE, or cDCE degradation, and no bacterial growth was observed. Examination of the iron medium by X-ray diffraction and scanning electron microscopy did not indicate the presence of precipitate on the reactive material.

Source: Gillham 1996.

B.3 Industrial Facility, Kansas

B.3.1 Project Description

A groundwater investigation during the early 1990s identified a TCE plume, with concentrations ranging from 100 to 400 ppb ($\mu\text{g/L}$), egressing from an industrial facility in Kansas. The TCE occurs in a basal alluvial sand and gravel zone overlying the local bedrock, at a depth of about 30 feet below ground surface. In mid-1995, a

treatability study was conducted on groundwater from the facility to determine the effectiveness of granular iron in degrading chlorinated organic compounds in the groundwater.

The treatability study consisted of pumping groundwater from the site through a laboratory column containing the iron material. The column test provided site-specific information on (1) the dechlorination rate of TCE; (2) the potential for the formation and degradation of chlorinated by-products; and (3) potential inorganic chemical changes. The results of this study were used to determine the required residence time necessary for the dechlorination of TCE and its degradation products.

A groundwater model of the site was then generated, incorporating various funnel and gate configurations. This model helped to determine the size of the in-situ system necessary to capture and treat the plume of contaminated groundwater, and to estimate the expected groundwater velocity through the gate. The velocity estimate, together with the required residence time determined from the treatability study, were used to determine the necessary thickness of the iron section in the gate.

During December 1995 through January 1996 a 1,000-foot-long funnel and gate system was installed at the facility property boundary. A low natural groundwater velocity permitted the use of a high funnel-to-gate ratio; the velocity increase due to the funneling action permitted a reasonably small treatment zone to be built. The system was constructed with about 490 feet of impermeable funnel on either side of a 20-foot long reactive gate. Construction of the funnel sections was accomplished by first constructing a single, soil-bentonite slurry wall. After the wall had set, the 20-foot gate section was excavated in the middle of the wall. The iron zone was then installed in the gate section, measuring about 13 feet deep and about 3-foot wide (that is, the flow-through thickness was 3 feet). Weather delays and other non-technical delays extended the construction period; however, the construction contractor estimated that under optimal conditions the slurry wall could have been built in two weeks, and the reactive gate section in one week.

B.3.2 Results

Costs for the installation (slurry walls and gate) were about \$400,000, including 70-tons of granular, reactive iron.

Results to date show nondetectable concentrations of VOCs in the wells screened in the gate. For further details see Focht, Vogan, and O'Hannesin 1996.

Sources: ETI 1996; Focht, Vogan, and O'Hannesin 1996.

B.4 U.S. Coast Guard Facility, North Carolina

In June 1996, an in-situ reactive wall was installed near a former machine shop at a U.S. Coast Guard facility in Elizabeth City, North Carolina, using a continuous trenching technique, to treat a groundwater contaminant plume with TCE concentrations of about 10 mg/L and hexavalent chromium also at about 10 mg/L. The reactive wall measures about 150 feet in length, 2 feet in width, and extends to about 26 feet bgs.

For excavation, continuous trenching was performed with a cutting chain excavating system, similar to a Ditch Witch™. As the chain excavator moved across the designated trench boundary, soils were brought to the surface and deposited onto the ground surface. The soils were eventually analyzed for hazardous constituents and removed from the site. A steel trench box, extending to the width and depth of the trench, was pulled immediately behind the chain excavator and served to keep the trench open and allow the emplacement of granular iron into the trench. Through a hopper above the trench box, granular iron was fed into and through the trench box to the excavated area. This process, which involved the placement of about 450 tons of iron, was continued for the entire length of the trench and was completed in a single day. Total cost of the installation was about \$500,000 with the iron costing just under \$400 per ton.

Source: Blowes and others 1997; ETI 1996

B.5 Lakewood Colorado Facility

The largest in-situ funnel and multiple gate system to date was installed from July through November 1996 at a government facility in Lakewood, Colorado. The facility is underlain by unconsolidated sediment and bedrock aquifers, with the bedrock surface at about 25 feet bgs. Groundwater contamination at the facility, mainly VOCs, is present in both aquifers at varying concentrations (TCE and DCE: 700 µg/L maximum; vinyl chloride: 15 µg/L maximum), and over a widespread area.

A sheet piling wall, which serves as the funnel for this system, was installed over a length of 1,040 feet and to a depth of 25 feet bgs. Four 40-foot long reactive gate sections with varying thicknesses were installed at designated locations along the wall. Varying gate section thicknesses were used to compensate for variations in groundwater flow velocities and VOC concentrations in different parts of the site. In accomplishing the funnel installations, sheet piling boxes were erected at each location and native material was excavated from inside each box. A thin layer of pea gravel was then placed at the bottom of each excavation followed by granular iron up to about 9 to 13 feet bgs.

Groundwater flow velocities are expected to range from less than 1 foot per day (ft/day) to about 10 ft per day; data collection is currently underway to determine these. Initial monitoring data indicate that effluent contaminant concentrations are meeting the design criteria.

Source: ETI 1996.

B.6 References

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Appendix C
Analytical Data Tables

Table C-I. Summary of Analytical Data-June

SAMPLE Data	MW-U1 06/07/95	MW-U2 06/08/95	MW-U3 06/07/95	MW-FE1 06/07/95	MW-FE2 06/08/95	MW-FE3 06/07/95	MW-D1 06/07/95	MW-D2 06/08/95	MW-D3 06/07/95	MW-D4 06/07/95	MW-D5 06/08/95	MW-D6 06/07/95
SUBSTANCE DETECTED												
VOCs (micrograms/liter):												
Acetone	5.0U	5.0U	5.0U	5.0U	12	13	13	12	9.5	NA	NA	NA
Chloroform	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	NA	NA	NA
1,1-Dichloroethane	1.5	1.9	1.1	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	NA	NA	NA
cis-1,2-dichloroethene	160	220	120	1.0U	1.6	1.0U	24	38	30	NA	NA	NA
trans-1,2-dichloroethene	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	NA	NA	NA
Tetrachloroethene	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	NA	NA	NA
1,1,1-Trichloroethane	4.6	6.5	3.2	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	NA	NA	NA
Trichloroethene	130	170	74	1.0U	1.0U	1.0U	5.7	7.3	6.8	NA	NA	NA
Vinyl chloride	7.1	6.3	4.9	1.0U	1.0U	1.0U	1.3	2.1	1.6	NA	NA	NA
Tentatively Identified Compounds (total)	3J	3J	2J	3J	3J	13J	1J	3J	U	NA	NA	NA
Metals (milligrams/liter):												
Aluminum	2.96	1.5	3.32	0.1U	2.37	0.1U	0.561	1.02	1.14	7.08	0.313	1.25
Barium	0.0227	0.02U	0.02U	0.535	0.521	0.723	0.02U	0.02U	0.02U	0.142	0.04	0.0934
Calcium	71.3	66.7	93	12.8	18.6	12.9	1a.9	20.5	17.6	126	55.5	66.8
Chromium	0.01U	0.01U	0.01U	0.0155	0.0172	0.01U	0.01U	0.01 u	0.01U	0.0113	0.01U	0.01U
Copper	0.02U	0.02U	0.02U	0.0422	0.0361	0.02U	0.02U	0.02U	0.02U	0.02U	0.02U	0.02U
Iron	4.49	2.42	6.34	16.6	27.8	5.47	0.823	1.12	1.42	10.9	0.794	2.08
Lead	0.005U	0.005U	0.05U	0.005U	0.005U	0.005U	0.005U	0.005U	0.0296	0.00947	0.005U	0.005U
Magnesium	11.2	10.0	14.9	5.7	4.02	7.31	2.82	3.13	2.69	34.9	7.38	12.8
Manganese	0.415	0.241	0.393	0.245	0.56	0.182	0.202	0.142	0.186	1.21	0.512	1.02
Potassium	2.05	1.59	2.68	1.54	2.26	1.53	1.09	1.0U	1.22	2.77	1.25	1.68
Sodium	29.2	27.4	30.7	36.4	36.1	35.2	32.8	29	29.3	27.6	25.1	26.2
Zinc	0.0216	0.0146	0.0277	0.01U	0.0205	0.01 u	0.01U	0.0104	0.0229	0.0525	0.0206	0.0118
Wet Chemistry (milligrams/liter):												
Bicarbonate Alkalinity	167	162	139	17.2	18.5	34.1	41.4	42.4	40.4	NA	NA	NA
Chloride	48	49	48.4	53.8	53.7	53	52.2	47.8	45.7	NA	NA	NA
Nitrate/Nitrite Nitrogen	0.529	0.57	0.332	0.0591	0.0609	0.0579	0.05U	0.05U	0.05U	NA	NA	NA
Nitrate Nitrogen	0.47	0.525	0.307	0.0591	0.0501	0.0579	0.05U	0.05U	0.05U	NA	NA	NA
Nitrite Nitrogen	0.0591	0.0451	0.0251	0.01U	0.0108	0.01U	0.0197	0.0133	0.01U	NA	NA	NA
sulfate	19	20.8	19.1	18.8	21.2	1a.1	18.1	1a.7	16.6	NA	NA	NA
Total Phospholipid Fatty Acids:												
(Average; picomoles/liter)*	22,188	14,865	45,310	34,166	29,550	21,065	43,233	13,781	17,084	1,985	1,908	1,942

Notes:

U = substance not detected; associated value is the reported detection limit

NA = parameter not analyzed

• Average value of replicate samples

J = estimated concentration

Table C-2. Summary of Analytical Data-July

SAMPLE Date	MW-U1 07/13/95	MW-U2 07/12/95	MW-U3 07/11/95	MW-FE1 07/13/95	MW-FE2 07/12/95	MW-FE3 07/11/95	MW-D1 07/13/95	MW-D2 07/12/95	MW-D3 07/11/95	MW-D4 07/13/95	MW-D5 07/12/95	MW-D6 07/11/95
SUBSTANCE DETECTED												
VOCs (micrograms/liter):												
Acetone	5.0U	5.0U	5.0U	12	5.0U	9.6	8.4	24	30	5.0U	44	NA
Chloroform	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	NA
1,1-Dichloroethane	3.5	2.8	3.1	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	NA
cis-1,2-Dichloroethene	230	280	360	LOU	1.0U	1.0U	2.2	3.7	3.9	30	50	NA
trans-1,2-Dichloroethene	1.2	1.0U	1.0	1.0U	1.0U	1.00	1.0U	1.0U	1.0U	1.0U	1.0U	NA
Tetrachloroethene	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	NA
1,1,1-Trichloroethane	1.0U	4.5	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	NA
Trichloroethene	100	160	280	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	29	54	NA
Vinyl chloride	73	16	18	1.0U	1.0U	1.2	1.0U	1.0U	1.0U	1.0U	2.2	NA
Tentatively Identified Compounds (Total)	3J	9J	2J	1U	6J	1J	1U	8J	1U	1U	2J	NA
Metals (milligrams/liter):												
Aluminum	0.10U	0.10U	0.155	0.10U	0.10U	0.1U	0.10U	0.17	0.107	0.153	0.10U	0.11
Barium	0.0374	0.0268	0.02U	0.241	0.522	0.161	0.0739	0.02U	0.0494	0.02U	0.0246	0.035
Calcium	90.8	88.8	88	14.5	14.3	15	22.6	13.7	17.6	21.3	36	30.2
Chromium	0.01U	0.01U	0.01U	0.01U	0.01U	0.01U	0.01U	0.01U	0.01U	0.01U	0.01U	0.01U
Copper	0.02U	0.02U	0.02U	0.02U	0.02U	0.02U	0.02U	0.02U	0.02U	0.02U	0.02U	0.02U
Iron	0.0784	0.05U	0.184	0.41	0.252	0.615	0.0883	0.05U	0.0571	0.174	0.05U	0.104
Lead	0.05U	0.05U	0.05U	0.05U	0.05U	0.05U	0.05U	0.05U	0.05U	0.05U	0.05U	0.05U
Magnesium	12.6	12.3	12.5	10.8	10.2	11.3	7.06	2.87	6.18	2.96	4.91	4.74
Manganese	0.559	0.427	0.281	0.24	0.111	0.312	0.243	0.127	0.222	0.156	0.312	0.516
Potassium	1.0U	1.0U	1.0U	1.65	1.45	1.66	1.42	1.0U	1.36	1.0U	1.0U	1.0U
Sodium	31.8	31	31.4	30	30.9	30.8	30.2	27.5	28.8	27.9	26.7	28.2
Zinc	0.0198	0.0253	0.0268	0.01U	0.0109	0.0113	0.0129	0.0115	0.0124	0.01U	0.0161	0.0144
Wet Chemistry (milligrams/liter):												
Bicarbonate Alkalinity	188	278	290	39.4	55.6	63	84.8	51.5	48	NA	NA	NA
Chloride	52.8	53.2	53.2	52.1	54	53.3	51.8	48.6	51.4	NA	NA	NA
Nitrate/Nitrite Nitrogen	0.338	0.378	0.383	0.05U	0.05U	0.05U	0.05U	0.05U	0.05U	NA	NA	NA
Nitrate Nitrogen	0.338	0.05U	0.383	0.05U	0.05U	0.05U	0.05U	0.05U	0.05U	NA	NA	NA
Nitrite Nitrogen	0.01U	0.378	0.01U	0.01U	0.01U	0.01U	0.01U	0.01U	0.01U	NA	NA	NA
Sulfate	16.7	17.1	16.7	15.6	16.1	14.9	11.8	5.1	14.2	NA	NA	NA
Total Phospholipid Fatty Acids:												
(Average: picomoles/liter)*	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA

Notes:

U = substance not detected; associated value is detection limit.

• Average value of replicate samples

NA = parameter not analyzed.

J = estimated concentration.

VOC sample fractions were collected from wells MW-D4 and D5 for the sole purpose of supporting the demonstration health and safety program, and were not required by the project quality assurance project plan;

VOC data from these wells are not directly relevant to demonstration objectives.

Table C-3. Summary of Analytical Data-August

SAMPLE	MW-U1	MW-U2	MW-U3	M w - F E 1	MW-FE2	MW-FE3	MW-D1	MW-D2	MW-D3	MW-D4	MW-D5	M W - D 6
Date	08/08/95	08/09/95	08/08/95	08/08/95	08/09/95	08/08/95	08/08/95	08/09/95	08/08/95	08/08/95	08/09/95	08/08/95
SUBSTANCE DETECTED												
VOCs (micrograms/liter):												
Acetone	5.0U	8	5.0U	5.0U	8	7.7	7.6	5.0U	5.0U	NA	NA	NA
Chloroform	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	NA	NA	NA
1,1-Dichloroethane	2.4	2.2	3.3	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	NA	NA	NA
cis-1,2-Dichloroethene	180	190	550	1.0U	1.1	1.0U	6	1.6	1.9	NA	NA	NA
trans-1,2-Dichloroethene	1.0U	1.0U	2.2	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	NA	NA	NA
Tetrachloroethene	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	NA	NA	NA
1,1,1-Trichloroethane	4.5	3.8	6.3	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	NA	NA	NA
Trichloroethene	110	110	330	1.0U	1.0U	1.0U	3.3	1.0U	1.0U	NA	NA	NA
Vinyl chloride	8.1	4.7	21	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	NA	NA	NA
Tentatively Identified Compounds (Total)	2.0J	5.0J	2.0J	1.0U	1.0J	5.01	2.0J	3.01	1.0U	NA	NA	NA
Metals (milligrams/liter):												
Aluminum	0.149	0.145	0.10U	0.10U	0.10U	0.10U	0.109	0.122	0.11	1.12	0.112	0.506
Barium	0.0385	0.0303	0.02U	0.281	0.384	0.08	0.0655	0.02U	0.0462	0.02U	0.0281	0.045
Calcium	86.3	89.8	88.8	9.42	10.6	10.4	21.9	16.8	13.9	22.4	32.4	24.9
Chromium	0.01U	0.01U	0.01U	0.01U	0.01U	0.01U	0.01U	0.01U	0.01U	0.01U	0.01U	0.01U
Copper	0.02U	0.02U	0.02U	0.02U	0.02U	0.02U	0.02U	0.02U	0.02U	0.02U	0.02U	0.02U
Iron	0.146	0.166	0.05%	0.406	0.311	1.16	0.108	0.10U	0.088	1.48	0.1U	0.676
Lead	0.05U	0.05U	0.05U	0.05U	0.05U	0.05U	0.05U	0.05U	0.05U	0.05U	0.05U	0.05U
Magnesium	12.2	12.5	12.6	10.3	9.60	10.7	6.28	4.62	5.23	4.06	4.76	5.01
Manganese	0.541	0.432	0.321	0.186	0.118	0.211	0.236	0.267	0.2	0.189	0.4	0.543
Potassium	2.23	1.44	2.46	1.96	1.26	2.18	1.6	1.0U	1.73	1.51	1.09	1.3
sodium	31.4	30.2	32	30.5	29.9	30.1	30.1	29.8	29.6	29.4	29.1	29.8
Zinc	0.0205	0.029	0.0184	0.01U	0.0111	0.01U	0.0127	0.0153	0.0102	0.0156	0.0208	0.0148
wet Chemistry (milligrams/liter):												
Bicarbonate Alkalinity	293	293	298	68.7	59.9	73.9	92.9	65.6	64.3	NA	NA	NA
Chloride	54.4	56.4	54.9	55.7	55.7	55.2	54.2	53.7	54.7	NA	NA	NA
Nitrate/Nitrite Nitrogen	0.277	0.3%	0.34	0.05U	0.05U	0.05U	0.053	0.05U	0.05U	NA	NA	NA
Nitrate Nitrogen	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Nitrite Nitrogen	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
sulfate	18.1	17.2	18	5.0U	6.33	5.0U	5.0U	5.0U	5.0U	NA	NA	NA
Total Phospholipid Fatty Acids:												
(Average; picomoles/liter)*	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA

Notes:

U = substance not detected; associated value is detection limit.

NA = parameter not analyzed.

* Average value of replicate samples.

J = estimated value.

Table C-4. Summary of Analytical Data-October

SAMPLE Date	MW-U1 10/11/95	MW-U2 10/12/95	MW-U3 10/11/95	MW-FE1 10/11/95	MW-FE2 10/12/95	MW-FE3 10/11/95	MW-D1 10/11/95	MW-D2 10/12/95	MW-D3 10/11/95	MW-D4 10/11/95	M W - D 5 10/12/95	MW-D6 10/11/95
SUBSTANCE DETECTED												
VOCs (micrograms/liter):												
Acetone	5.0U	5.0U	5.0U	5.0U	5.0U	5.0U	5.6	5.0U	5.0U	NA	NA	NA
Bromodichloromethane	LOU	LOU	LOU	LOU	LOU	LOU	LOU	LOU	LOU	NA	NA	NA
Chloroform	LOU	LOU	LOU	LOU	LOU	LOU	LOU	LOU	LOU	NA	NA	NA
Chloroethane	LOU	LOU	2	LOU	LOU	LOU	LOU	LOU	LOU	NA	NA	NA
1,1-Dichloroethane	3.9	5.4	5.8	LOU	LOU	2.2	LOU	LOU	LOU	NA	NA	NA
1,1-Dichloroethene	1.1	1.2	1.2	LOU	LOU	LOU	LOU	LOU	LOU	NA	NA	NA
cis-1,2-Dichloroethene	320	450	370	1.2	2	3.8	5	7.5	2	NA	NA	NA
trans-1,2-Dichloroethene	1.7	1.9	1.9	LOU	LOU	LOU	LOU	LOU	LOU	NA	NA	NA
Methylene Chloride	LOU	LOU	LOU	LOU	LOU	LOU	LOU	LOU	LOU	NA	NA	NA
Tetrachloroethene	LOU	LOU	LOU	LOU	LOU	LOU	LOU	LOU	LOU	NA	NA	NA
1,1,1-Trichloroethane	5.6	7.7	7.9	LOU	LOU	LOU	LOU	LOU	LOU	NA	NA	NA
Toluene	LOU	LOU	LOU	LOU	LOU	LOU	LOU	LOU	LOU	NA	NA	NA
Trichloroethene	120	160	150	LOU	LOU	LOU	1.2	1.5	LOU	NA	NA	NA
Vinyl chloride	53	79	49	LOU	LOU	2.3	LOU	LOU	LOU	NA	NA	NA
Tentatively Identified Compounds (Total)	LOU	LOU	LOU	2.5J	3.6J	3.31	LOU	LOU	LOU	NA	NA	NA
Metals (milligrams/liter):												
Aluminum	0.1U	0.1U	0.1U	0.1U	0.1U	0.1U	0.1U	0.1U	0.1U	0.17	0.1U	0.712
Barium	0.0402	0.0305	0.02U	0.0599	0.14	0.02U	0.05	0.02U	0.0386	0.132	0.0454	0.0258
Calcium	92.1	95.6	88.11	7.72	9.17	9.61	21.3	15	15	64.8	28.6	30.2
Chromium	0.0321	0.03U	0.01U	0.03U	0.03U	0.03U	0.03U	0.03U	0.03U	0.038	0.03U	0.03U
Copper	0.02U	0.02U	0.02U	0.02U	0.02U	0.02U	0.02U	0.02U	0.02U	0.02U	0.02U	0.02U
Iron	0.1U	0.1U	0.1U	0.184	0.203	0.523	0.1U	0.10U	0.1U	1.16	0.233	0.541
Lead	0.05U	0.05U	0.05U	0.05U	0.05U	0.05U	0.05U	0.05U	0.05U	0.05U	0.05U	0.05U
Magnesium	12	12.3	12.6	9.01	9.68	10.5	5.51	4.25	5.01	9.08	4.4	5.16
Manganese	0.59	0.461	0.321	0.0716	0.079	0.0706	0.231	0.194	0.23	1.36	0.719	0.321
Potassium	1.99	1.78	2.46	2.22	2.17	2.22	1.7	1.39	1.72	1.18	1.05	1.52
Sodium	31.1	31.4	32	33.3	33.9	33.1	32.5	32.8	32.9	33.5	33	34.8
Zinc	0.02U	0.02U	0.0184	0.02U	0.02U	0.02U	0.02U	0.02U	0.02U	0.02U	0.02U	0.02U
wet Chemistry (milligrams/liter):												
Bicarbonate Alkalinity	299	299	299	55.8	60	65.7	n.7	64.7	59.8	NA	NA	NA
Chloride	45.4	46.4	48	47.6	49.5	48.4	48.7	48.7	49	NA	NA	NA
Nitrate/Nitrite Nitrogen	0.19	0.31	0.269	0.05U	0.05U	0.05U	0.05U	0.05U	0.05U	NA	NA	NA
Nitrate Nitrogen	0.19	0.298	0.269	0.05U	0.05U	0.05U	0.05U	0.05U	0.05U	NA	NA	NA
Nitrite Nitrogen	0.01U	0.0118	0.01U	0.01U	0.01U	0.01U	0.01U	0.01U	0.01U	NA	NA	NA
Sulfate	15.8	15.5	16.7	5.0U	5.0U	5.0U	5.0U	5.0U	5.0U	NA	NA	NA
Total Phospholipid Fatty Acids:												
(Average, picomoles/liter)*	91	115	492	56	36	20	438	325	245	1,774	602	565

87

Notes:

U = substance not detected.

• Average value of replicate sample&

NA = parameter not analyzed.

J = estimated value.

Table C-5. Summary of Analytical Data-November

SAMPLE Date	MW-U1 11/09/95	MW-U2 11/08/95	MW-U3 11/08/95	Mw-FE1 11/09/95	Mw-FE2 11/08/95	MW-FE3 11/08/95	MW-D1 11/08/95	MW-D2 11/08/95	MW-D3 11/08/95	MW-D4 11/09/95	MW-D5 11/08/95	MW-D6 11/08/95
SUBSTANCE DETECTED												
VOCs (micrograms/liter):												
Acetone	5.0U	5.0U	5.0U	5.0U	5.0U	5.0U	5.0U	5.0U	8	WA	NA	NA
Bromodichloromethane	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	NA	NA	NA
Chloroform	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	NA	NA	NA
Chloroethane	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	NA	NA	NA
1,1-Dichloroethane	1.1	1.8	2.7	1.0U	1.0U	3.9	1.0U	1.0U	1.0U	NA	NA	NA
1,1-Dichloroethene	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	NA	NA	NA
cis-1,2-Dichloroethene	98	140	240	1.0U	1.0U	15	4.6	4.2	2.8	NA	NA	NA
trans-1,2-Dichloroethene	1.0U	1.0U	1.9	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	NA	NA	NA
Methylene Chloride	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	1.3	NA	NA	NA
Tetrachloroethene	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	NA	NA	NA
1,1,1-Trichloroethane	3.3	4.4	6.9	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	NA	NA	NA
Toluene	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	NA	NA	NA
Trichloroethene	32	65	110	1.0U	1.0U	1.0U	1.6	1.0U	1.0U	NA	NA	NA
Vinyl chloride	7.9	10	25	1.0U	1.0U	1.6	1.0U	1.0U	1.0U	NA	NA	NA
Tentatively Identified Compounds (Total)	8.0U	8.41	7.11	4.31	2.0U	3.81	1.0U	2.03	1.0U	NA	NA	NA
Metals (milligrams/liter):												
Aluminum	0.2U	0.2U	0.2U	0.2U	0.2U	0.2U	0.2U	0.2U	0.02U	0.735	0.2U	0.435
Barium	0.0342	0.0284	0.02U	0.0492	0.0974	0.02U	0.0422	0.02U	0.0341	0.0275	0.0333	0.0572
Calcium	87.5	89.9	89.9	8.12	7.96	8.88	20.3	13.4	10.3	33.3	30.3	39.3
Chromium	0.01U	0.01U	0.01U	0.01U	0.01U	0.01U	0.01U	0.01U	0.01U	0.01U	0.01U	0.01U
Copper	0.02U	0.02U	0.02U	0.02U	0.02U	0.02U	0.02U	0.02U	0.02U	0.02U	0.02U	0.02U
Iron	0.165	0.0728	0.0506	0.144	0.2	0.506	0.134	0.0862	0.134	1.1	0.211	0.498
Lead	0.05U	0.05U	0.05U	0.05U	0.05U	0.05U	0.05U	0.05U	0.05U	0.05U	0.05U	0.05U
Magnesium	11.9	11.9	12	8.38	8.06	10.3	4.76	3.72	4.27	5.58	4.56	6.72
Manganese	0.468	0.345	0.269	0.0534	0.0598	0.0453	0.161	0.161	0.0733	0.34	0.452	0.521
Potassium	1.65	1.75	1.49	2.01	1.86	1.93	1.23	1.27	1.4	1.26	1.0U	1.38
Sodium	28	27.7	28.7	27.7	28.2	28.1	23.7	23.2	22.5	21.1	22.1	24.8
Zinc	0.02U	0.02U	0.02U	0.02U	0.02U	0.02U	0.02U	0.02U	0.02U	0.02U	0.02U	0.02U
wet Chemistry (milligrams/liter):												
Bicarbonate Alkalinity	259	272	283	41.8	44.3	50.3	55.5	63.7	48.8	NA	NA	NA
Chloride	40.8	42.5	43.8	43.6	45.8	42.6	37.6	37.9	38.7	NA	NA	NA
Nitrate/Nitrite Nitrogen	0.125	0.175	0.19	0.05U	0.05U	0.05U	0.05U	0.05U	0.05U	NA	NA	NA
Nitrate Nitrogen	0.11	0.157	0.171	0.05U	0.05U	0.05U	0.05U	0.05U	0.05U	NA	NA	NA
Nitrite Nitrogen	0.153	0.018	0.0192	0.01U	0.01U	0.01U	0.01U	0.01U	0.01U	NA	NA	NA
Sulfate	13.1	14.4	15.3	5.0U	5.0U	5.0U	5.0U	5.0U	5.0U	NA	NA	NA
Total Phospholipid Fatty Acids:												
(Average: picomoles/liter)*	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA

Notes

U = substance not detected; associated value is detection limit.

NA = parameter not analyzed.

* Average value of replicate samples.

J = estimated value.

Table C-6. Summary of Analytical Data-December

SAMPLE Date	Mw-U1 12/05/95	MW-U2 12/06/95	MW-U3 12/05/95	MW-FE1 12/05/95	MW-FE2 12/06/95	MW-FE3 12/05/95	MW-D1 12/05/95	MW-D2 12/06/95	MW-D3 12/05/95	MW-D4 12/05/95	MW-D5 12/06/95	MW-D6 12/05/95
SUBSTANCE DETECTED												
VOCs (micrograms/liter):												
Acetone	5.0U	5.0U	5.0U	5.0U	5.0U	5.0U	5.0U	5.0U	5.0U	5.0U	NA	NA
Bromodichloromethane	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	NA	NA
chloroform	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	NA	NA
Chloroethane	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	NA	NA
1,1-Dichloroethane	3.4	3.6	3.9	1.0U	1.0U	2.1	1.0U	1.0U	1.0U	1.0U	NA	NA
1,1-Dichloroethene	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	NA	NA
cis-1,2-Dichloroethene	180	240	270	1.0U	1.0U	4.3	2.5	5.6	5.4	NA	NA	NA
trans-1,2-Dichloroethene	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	NA	NA
Methylene Chloride	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	NA	NA
Tetrachloroethene	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	NA	NA
1,1,1-Trichloroethane	13	11	13	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	NA	NA
Toluene	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	1.0U	NA	NA
Trichloroethene	110	120	130	1.0U	1.0U	1.0U	1.0U	0.913	1.0U	1.0U	NA	NA
Vinyl chloride	21	22	22	1.0U	1.0U	4.1	1.0U	1.0U	1.0U	1.0U	NA	NA
Tentatively Identified Compounds (Total)	4.13	3.63	4.43	2.0U	3.21	3.21	1.33	6.2U	1.0U	1.0U	NA	NA
Metals (milligrams/liter):												
Aluminum	0.2U	0.2U	0.2U	0.2U	0.2U	0.2U	0.2U	0.2U	0.02U	0.325	0.2U	0.974
Barium	0.0387	0.0252	0.02U	0.0474	0.102	0.02U	0.0363	0.02U	0.0411	0.0231	0.0338	0.0578
Calcium	92.5	90.6	90.7	12.7	9.6	9.98	21	15.4	16.6	28.5	33.6	43.0
Chromium	0.01U	0.01U	0.01U	0.01U	0.01U	0.01U	0.01U	0.01U	0.01U	0.01U	0.01U	0.01U
Copper	0.02U	0.02U	0.02U	0.02U	0.02U	0.02U	0.02U	0.02U	0.02U	0.02U	0.02U	0.02U
Iron	0.1U	0.1U	0.1U	0.238	0.158	0.601	0.148	0.1U	0.128	0.554	0.159	1.06
Lead	0.05U	0.05U	0.05U	0.05U	0.05U	0.05U	0.05U	0.05U	0.05U	0.05U	0.05U	0.05U
Magnesium	12.9	12.7	12.9	10.4	7.33	8.29	5.5	4.23	6.65	4.96	5.95	8.47
Manganese	0.494	0.388	0.289	0.0958	0.0574	0.128	0.16	0.195	0.238	0.318	0.174	0.377
Potassium	1.87	1.93	1.97	2.11	1.86	1.5	1.47	1.02	1.78	1.16	1.0U	1.23
Silver	0.01U	0.01U	0.01U	0.01U	0.01U	0.01U	0.01U	0.01U	0.01U	0.01U	0.01U	0.01U
sodium	30.5	29.4	30.3	29.9	29.6	28.6	26.5	23.4	27.1	20	15.5	23.9
z 11	0.0129	0.0119	0.0125	0.01U	0.01U	0.01U	0.01U	0.01U	0.01U	0.0114	0.0115	0.014
wet Chemistry (milligrams/liter):												
Bicarbonate Alkalinity	311	291	293	9.95	47.8	43.8	75.7	56.5	61.8	NA	NA	NA
Chloride	47.2	47.4	48	48.3	49.2	48.6	45.3	42.8	45.8	NA	NA	NA
Nitrate/Nitrite Nitrogen	0.23	0.269	0.19	0.05U	0.05U	0.05U	0.05U	0.05U	0.05U	NA	NA	NA
Nitrate Nitrogen	0.2	0.238	0.169	0.05U	0.05U	0.05U	0.05U	0.05U	0.05U	NA	NA	NA
Nitrite Nitrogen	0.0299	0.0305	0.0209	0.01U	0.01U	0.01U	0.01U	0.01U	0.01U	NA	NA	NA
sulfate	16.3	17.2	16.3	5.0U	5.0U	5.0U	5.0U	5.0U	5.0U	5.0U	NA	NA
Total Phospholipid Fatty Acids:												
(Average; picomoles/liter)*	19	66	54	10	72	114	1.005	1.508	1.601	2.480	3.450	2.482

Notes:

U = substance not detected; associated value is detection limit.

NA = parameter not analyzed.

J = estimated concentration; reported value is below PQL.

• Average value of replicate samples.